

# *HST*/COS observations of a new population of associated QSO absorbers <sup>★</sup>

S. Muzahid<sup>1†</sup>, R. Srianand<sup>1</sup>, N. Arav<sup>2</sup>, B. D. Savage<sup>3</sup> and A. Narayanan<sup>4</sup>

<sup>1</sup> *Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune 411 007, India*

<sup>2</sup> *Department of Physics, Virginia Tech, Blacksburg, VA, 24061, USA*

<sup>3</sup> *Department of Astronomy, University of Wisconsin, 475 North Charter Street, Madison, WI, 53706, USA*

<sup>4</sup> *Indian Institute of Space Science & Technology, Thiruvananthapuram 695547, Kerala, India*

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## ABSTRACT

We present a sample of new population of associated absorbers, detected through Ne VIII  $\lambda\lambda 770, 780$  absorption, in *HST*/COS spectra of intermediate redshift ( $0.45 < z < 1.21$ ) quasars (QSOs). Our sample comprised of total 12 associated Ne VIII systems detected towards 8 lines of sight (none of them are radio bright). The incidence rate of these absorbers is found to be 40%. Majority of the Ne VIII systems at small ejection velocities ( $v_{ej}$ ) show complete coverage of the background source, but systems with higher  $v_{ej}$  show lower covering fractions (i.e.  $f_c \leq 0.8$ ) and systematically higher values of  $N(\text{Ne VIII})$ . We detect Mg X  $\lambda\lambda 609, 624$  absorption in 7 out of the 8 Ne VIII systems where the expected wavelength range is covered by our spectra and is free of any strong blending. We report the detections of Na IX  $\lambda\lambda 681, 694$  absorption, for the first time, in three highest ejection velocity (e.g.  $|v_{ej}| \gtrsim 7,000 \text{ km s}^{-1}$ ) systems in our sample. All these systems show very high  $N(\text{Ne VIII})$  (i.e.  $> 10^{15.6} \text{ cm}^{-2}$ ), high ionization parameter (i.e.  $\log U \gtrsim 0.5$ ), high metallicity (i.e.  $Z \gtrsim Z_{\odot}$ ), and ionization potential dependent  $f_c$  values. The observed column density ratios of different ions are reproduced by multiphase photoionization (PI) and/or collisional ionization (CI) equilibrium models. While solar abundance ratios are adequate in CIE, enhancement of Na relative to Mg is required in PI models to explain our observations.

The column density ratios of highly ionized species (i.e. O VI, Ne VIII, Mg X etc.) show a very narrow spread. Moreover, the measured  $N(\text{Ne VIII})/N(\text{O VI})$  ratio in the associated absorbers is similar to what is seen in the intervening absorbers. All these suggest a narrow range of ionization parameter in the case of photoionization or a narrow temperature range (i.e.  $T \sim 10^{5.9 \pm 0.1} \text{ K}$ ) in the case of CIE models. The present data does not distinguish between these two alternatives. However, detection of absorption line variability with repeat *HST*/COS observations will allow us to (i) distinguish between these alternatives, (ii) establish the location of the absorbing gas and (iii) understand the mechanism that provides stability to the multiphase medium. These are important for understanding the contribution of associated Ne VIII absorbers to the AGN feedback.

**Key words:** galaxies:active – quasars:absorption lines – quasars:outflow

## 1 INTRODUCTION

Associated absorbers are unique tools to probe the physical conditions of the gaseous environment in the immediate vicinity of the background quasar (QSOs). The abundance of heavy elements

in these absorbers provides a direct measure of the star formation and chemical evolution in the center of galaxies hosting QSOs (Hamann 1997). Most importantly, good fraction of associated absorbers are believed to originate from the ejected material from the central engine of the QSOs (Richards et al. 1999). These outflows are theoretically invoked to regulate the star formation of the host galaxies and growth of the super massive black holes (SMBHs) at their centers (Silk & Rees 1998; King 2003; Bower et al. 2006; Ostriker et al. 2010).

There is no firm definition in the literature for an associated absorber. The absorbers with velocity spread of few  $\times 100 \text{ km s}^{-1}$ ,

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<sup>†</sup> E-mail: sowgat@iucaa.ernet.in

which appear within few  $\times 1000 \text{ km s}^{-1}$  from the emission redshift of the QSO, are generally defined to be associated absorbers (Hamann 1997). In addition to the proximity to the QSOs, associated absorbers are also characterized by (a) time variable absorption line strength (Barlow et al. 1989, 1992; Hamann et al. 1995; Srianand & Petitjean 2001; Hall et al. 2011; Vivek et al. 2012) (b) very high metallicity (e.g. near solar abundances; Petitjean et al. 1994; Hamann 1997) and high ionization parameter (e.g.  $\log U \gtrsim 0.0$ ; Hamann 1998; Hamann et al. 2000; Muzahid et al. 2012b) (c) partial coverage of the continuum source (e.g. Barlow et al. 1997; Srianand & Shankaranarayanan 1999; Ganguly et al. 1999; Arav et al. 2008) and (d) presence of excited fine structure lines (e.g. Srianand & Petitjean 2000). These above mentioned properties are unlikely to occur in intervening systems (however see Balashev et al. 2011, for a very special case) and thus, they are believed to originate from gas very close to the QSO or a possible ejecta of the central engine. In the case of gas outflowing from the QSO, line driven radiative acceleration has often been suggested to be an important driving mechanisms however, only a handful of convincing evidences exists in the literature till date (see e.g., Arav et al. 1994, 1995; Srianand et al. 2002).

Based on their line widths, the associated absorbers are broadly classified into two categories: (1) the broad absorption line (BAL) and (2) narrow absorption line (NAL) systems. BALs and NALs are predominantly detected through species (e.g., Mg II, C IV, Si IV, N V etc.) with low ionization potential (i.e.  $IP \lesssim 100 \text{ eV}$ ) in the UV-optical regime. On the other hand, the soft X-ray spectra of  $\sim 40 - 50\%$  of the Seyfert galaxies and QSOs happen to show K-shell absorption edges of highly ionized oxygen (i.e., O VII, O VIII with  $IP \gtrsim 0.5 \text{ keV}$ ; Reynolds 1997; George et al. 1998; Crenshaw et al. 2003), known as X-ray “warm absorbers” (WAs). These X-ray WAs are often said to correlate with the presence of absorption in the UV regime (see e.g., Mathur et al. 1994, 1995a,b, 1998, 1999; Brandt et al. 2000; Arav et al. 2007). Telfer et al. (1998) have argued that the BAL-like absorption seen towards SBS 1542+541 could be a potential X-ray WA candidate (see also Hamann et al. 1995). However, QSOs known to have associated BAL absorption are generally found to be X-ray weak (Green et al. 1995; Green & Mathur 1996; Stalin et al. 2011). In few cases the physical conditions in the UV absorbers are shown to be incompatible with that of X-ray WAs (e.g., Srianand 2000; Hamann et al. 2000). Therefore, although a unified picture of X-ray and UV associated absorbers is desirable, it is not clear whether there is any obvious connection between them. Even in cases, where simultaneous occurrences of the X-ray and UV absorption are seen, the absorbing gas need not be co-spatial. For example, envisaging a disk-wind model, Murray & Chiang (1995) have shown that the X-ray absorption originates very close to the accretion disk whereas UV absorption predominantly occurs in the accelerated gas farther away.

The study of the species with ionization potential intermediate between UV-optical and X-ray absorbers (i.e., few  $\times 100 \text{ eV}$ ) is important to understand the comprehensive nature of the ionization structure and thus the unified picture of QSO outflows detected in different wavebands. The resonant transitions of highly ionized species (e.g. Ne VIII, Na IX, Mg X, Al XI and Si XII), that fall in the far-ultraviolet (FUV) regime, are ideally suited for studying the intermediate ionization conditions of the associated absorbers. However, only a handful of absorbers showing some of these species have been reported till date. For example, the first tentative detection of associated Ne VIII absorption was reported by Korista et al. (1992) towards

Q 0226–1024. The three other tentative detections existing in literature are by Petitjean et al. (1996) towards HS 1700+6414, Gupta et al. (2005) towards 3C 48 and Ganguly et al. (2006) towards HE 0226–4110. We also note that a possible Ne VIII detection is reported in the composite *Far-Ultraviolet Spectroscopic Explorer (FUSE)* spectrum by Scott et al. (2004). There are only six confirmed detections of Ne VIII absorption in associated absorbers reported till date [i.e., UM 675, Hamann et al. (1995); SBS 1542+541, Telfer et al. (1998); PG 0946+301, Arav et al. (1999b); J2233–606, Petitjean & Srianand (1999); 3C 288.1, Hamann et al. (2000); HE 0238–1904, Muzahid et al. (2012b)]. Among these, both SBS 1542+541 and PG 0946+301 are BALQSOs. While multiphase photoionization models are generally used to explain most of these observations, Muzahid et al. (2012b) have shown that the models of collisional ionization equilibrium can also reproduce the observed column density ratios of high ions like O VI, Ne VIII and Mg X. Therefore the collisional ionization could be an equally important ionizing mechanism in these absorbers.

Although the highly ionized UV absorbers are of prime interest to probe the “missing link” between UV and X-ray continuum absorbers, the low rest frame wavelengths (i.e.  $\lambda_{\text{rest}} < 912 \text{ \AA}$ ) of the diagnostic species (e.g. Ne VIII, Na IX, Mg X etc.) make them difficult to detect. This is partly because of the Galactic Lyman-limit absorption in the spectra of low redshift sources and the Ly $\alpha$  forest contamination in the spectra of high redshift sources. Hence the intermediate redshift (i.e.  $0.5 < z_{\text{em}} < 1.5$ ) UV bright QSOs are ideal for this study. Note that such a study is only feasible with far-ultra-violet (FUV) sensitive space based telescopes like *Hubble Space Telescope (HST)*. In this paper we present a sample of new class of associated absorbers detected through Ne VIII absorption in the FUV spectra of intermediate redshift QSOs obtained with the *Cosmic Origins Spectrograph (COS)* on board *HST*.

This paper is organized as follows. In Section 2 we describe the observations and data reduction techniques for the sample of QSOs studied here. In Section 3 we discuss the effects of partial coverage in column density measurements and how we correct for it. Data sample and analysis of individual absorption systems are presented in Section 4. In Section 5 we explore ionization models for some of these systems detected with number of different ions. In Section 6 we discuss the overall properties of these absorbers. We summarize our main results in Section 7. Throughout this paper we use flat  $\Lambda$ CDM cosmology with  $(\Omega_M, \Omega_\Lambda) = (0.27, 0.73)$  and a Hubble parameter of  $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . The solar relative abundances of heavy elements are taken from Asplund et al. (2009).

## 2 OBSERVATIONS AND DATA REDUCTION

The sample in which we searched for Ne VIII absorbers had the following selection criteria: (1) archived *HST*/COS FUV spectra (G130M+G160M) of quasars which were public as of February 2012, (2) QSOs with emission redshift  $z_{\text{em}} \geq 0.45$  so that the the Ne VIII doublet transitions (770 $\text{\AA}$  and 780 $\text{\AA}$ ) are redshifted into the wavelength coverage of the COS G130M and G160M gratings, and (3) spectra with signal-to-noise ratio ( $S/N$ ) per resolution element  $> 10$ . The properties of COS and its in-flight operations are discussed by Osterman et al. (2011) and Green et al. (2012). The data were retrieved from the *HST* archive and reduced using the STScI CALCOS v.2.12 pipeline software. The reduced data were flux calibrated. The alignment and addition of the separate G130M and G160M exposures were done using the software developed by

**Table 1.** Details of observations of lines of sight where we search for associated Ne VIII absorption.

| No.<br>(1) | QSO<br>(2)      | $z_{\text{em}}$<br>(3)        | Grating<br>(4) | $t_{\text{exp}}$ (ks)<br>(5) | Coverage (Å)<br>(6) | Prop. ID<br>(7) | PI<br>(8)   |
|------------|-----------------|-------------------------------|----------------|------------------------------|---------------------|-----------------|-------------|
| 1.         | 3C 263*         | 0.646 (Marziani et al. 1996)  | G130M          | 15.3                         | 1140 – 1450         | 11541           | Green       |
|            |                 |                               | G160M          | 18.0                         | 1405 – 1790         |                 |             |
| 2.         | FBQS 0751+2919  | 0.916 (SDSS)                  | G130M          | 16.5                         | 1160 – 1465         | 11741           | Tripp       |
|            |                 |                               | G160M          | 23.2                         | 1410 – 1795         |                 |             |
| 3.         | HB89 0107–025   | 0.956 (Surdej et al. 1986)    | G130M          | 21.2                         | 1160 – 1465         | 11585           | Crighton    |
|            |                 |                               | G160M          | 21.1                         | 1410 – 1795         |                 |             |
| 4.         | HB89 0232–042*  | 1.440 (Janknecht et al. 2006) | G130M          | 16.0                         | 1160 – 1465         | 11741           | Tripp       |
|            |                 |                               | G160M          | 22.8                         | 1410 – 1795         |                 |             |
| 5.         | HE 0153–4520    | 0.451 (Wisotzki et al. 2000)  | G130M          | 5.2                          | 1140 – 1450         | 11541           | Green       |
|            |                 |                               | G160M          | 5.9                          | 1405 – 1790         |                 |             |
| 6.         | HE 0226–4110    | 0.493 (Ganguly et al. 2006)   | G130M          | 6.7                          | 1140 – 1450         | 11541           | Green       |
|            |                 |                               | G160M          | 7.7                          | 1405 – 1790         |                 |             |
| 7.         | HE 0238–1904    | 0.629 (Muzahid et al. 2012b)  | G130M          | 6.4                          | 1140 – 1450         | 11541           | Green       |
|            |                 |                               | G160M          | 7.4                          | 1405 – 1790         |                 |             |
| 8.         | HS 1102+3441    | 0.509 (SDSS)                  | G130M          | 11.3                         | 1140 – 1450         | 11541           | Green       |
|            |                 |                               | G160M          | 11.2                         | 1405 – 1790         |                 |             |
| 9.         | LBQS 0107–0235* | 0.957 (Surdej et al. 1986)    | G130M          | 28.2                         | 1140 – 1455         | 11585           | Crighton    |
|            |                 |                               | G160M          | 44.4                         | 1410 – 1795         |                 |             |
| 10.        | LBQS 1435–0134* | 1.310 (SDSS)                  | G130M          | 22.3                         | 1160 – 1465         | 11741           | Tripp       |
|            |                 |                               | G160M          | 34.1                         | 1410 – 1795         |                 |             |
| 11.        | PG 1148+549     | 0.975 (SDSS)                  | G130M          | 17.8                         | 1160 – 1465         | 11741           | Tripp       |
|            |                 |                               | G160M          | 18.4                         | 1410 – 1795         |                 |             |
| 12.        | PG 1206+459     | 1.163 (SDSS)                  | G130M          | 17.3                         | 1160 – 1465         | 11741           | Tripp       |
|            |                 |                               | G160M          | 36.1                         | 1410 – 1795         |                 |             |
| 13.        | PG 1259+593     | 0.476 (SDSS)                  | G130M          | 9.2                          | 1140 – 1450         | 11541           | Green       |
|            |                 |                               | G160M          | 11.1                         | 1405 – 1790         |                 |             |
| 14.        | PG 1338+416     | 1.214 (SDSS)                  | G130M          | 22.7                         | 1160 – 1465         | 11741           | Tripp       |
|            |                 |                               | G160M          | 35.0                         | 1410 – 1795         |                 |             |
| 15.        | PG 1407+265     | 0.940 (McDowell et al. 1995)  | G130M          | 16.6                         | 1160 – 1465         | 11741           | Tripp       |
|            |                 |                               | G160M          | 17.3                         | 1410 – 1795         |                 |             |
| 16.        | PG 1522+101     | 1.328 (SDSS)                  | G130M          | 16.4                         | 1160 – 1465         | 11741           | Tripp       |
|            |                 |                               | G160M          | 23.0                         | 1410 – 1795         |                 |             |
| 17.        | PG 1630+377     | 1.475 (SDSS)                  | G130M          | 22.9                         | 1160 – 1465         | 11741           | Tripp       |
|            |                 |                               | G160M          | 14.3                         | 1410 – 1795         |                 |             |
| 18.        | PKS 0405–123*   | 0.573 (Laor et al. 1994)      | G130M          | 22.1                         | 1140 – 1450         | 11508, 11541    | Noll, Green |
|            |                 |                               | G160M          | 11.0                         | 1405 – 1790         |                 |             |
| 19.        | PKS 0552–640*   | 0.680 (Grazian et al. 2002)   | G130M          | 9.2                          | 1140 – 1425         | 11692           | Howk        |
|            |                 |                               | G160M          | 8.2                          | 1400 – 1745         |                 |             |
| 20.        | PKS 0637–752*   | 0.653 (Hunstead et al. 1978)  | G130M          | 9.6                          | 1140 – 1425         | 11692           | Howk        |
|            |                 |                               | G160M          | 8.6                          | 1400 – 1745         |                 |             |

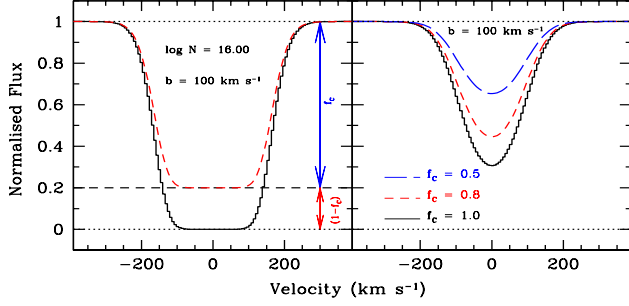
Notes – Column 2 and 3 list the name and emission redshift of the QSOs respectively. In the parenthesis we provide the references for emission redshift measurements. Column 4 lists the FUV gratings used for the observations. Column 5 is the total exposure time in kilo-seconds for each grating setting. Column 6 is the total wavelength coverage for the choice of grating. Column 7 lists the *HST* ID of the proposal for which the observations were carried out and; Column 8 lists the PI of the proposal. All data were retrieved from the *Mikulski Archive for Space Telescopes (MAST)* and reduced using the CALCOS pipeline v.2.12. \*Sources with 5 GHz flux density excess of 50 mJy.

the COS team<sup>1</sup>. The exposures were weighted by the integration time while coadding in flux units. The procedures followed for data reduction are described in greater detail in Narayanan et al. (2011). The unabsorbed QSO continuum is fitted using low-order polynomials interpolated between wavelength ranges devoid of strong absorption lines. We use the standard procedure that propagates the continuum placement uncertainty to the normalized flux.

The medium resolution ( $R \sim 20,000$ ) with  $S/N \geq 10$  COS data, covering 1150 – 1800 Å wavelength range, allow us to search for Ne VIII  $\lambda\lambda 770, 780$  doublets in the redshift range  $\sim 0.45 - 1.31$ . Observational details of our final sample of 20 quasar sight lines are listed in Table 1. Half of these sight lines were part of a blind

survey to detect the warm-hot intergalactic gas (prop. ID 11741). Of the remaining, majority are from the COS-GTO program (prop. ID 11541) to probe the gas phases in the low redshift IGM and galaxy halos. For the QSO PKS 0405–123, we have combined spectra obtained under the GTO program of the COS science team from December 2009 and the *HST* Early Release Observations (prop. ID 11508) of August 2009. While weak radio emission (i.e. flux density  $\leq 1$  mJy) is detected in most of the QSOs in our sample, only seven of them (called radio bright from now on) have radio flux density in excess of 50 mJy at 5 GHz.

<sup>1</sup> <http://casa.colorado.edu/~danforth/science/cos/costools.html>



**Figure 1.** Demonstration of the effect of partial coverage in case of a heavily saturated (left) and an unsaturated (right) Ne VIII lines. Partially covered saturated line will appear as flat bottom profile with nonzero flux. For a partially covered unsaturated line, column density measurement can lead to much lower value compared to the true value if we do not correct for the covering fraction.

### 3 PARTIAL COVERAGE AND UNCERTAINTY IN COLUMN DENSITY MEASUREMENT

Because of the close physical association between the background QSO and the associated absorber, in many cases it so happens that the latter does not cover the former entirely. In such cases, the observed residual intensity at any frequency can be written as,

$$I(\nu) = I_0(\nu)(1 - f_c) + f_c I_0(\nu) \exp[-\tau(\nu)]. \quad (1)$$

Here  $I_0(\nu)$  is the incident intensity,  $\tau(\nu)$  is the true optical depth, and  $f_c$  is the covering fraction. In the case of doublets with rest frame wavelengths  $\lambda_1$  &  $\lambda_2$  and oscillator strengths  $f_1$  &  $f_2$ , the residual intensities  $R_1$  and  $R_2$  in the normalized spectra, at any velocity  $v$  with respect to the line centroid are related by

$$R_2(v) = (1 - f_c) + f_c \times \left( \frac{R_1(v) - 1 + f_c}{f_c} \right)^\gamma, \quad (2)$$

where  $\gamma = f_2 \lambda_2 / f_1 \lambda_1$ . The value of  $\gamma$  is very close to 2 for doublets (see e.g., Srianand & Shankaranarayanan 1999; Petitjean & Srianand 1999). This equation in principle allows us to calculate the covering fraction of the absorbing gas.

The effects of partial coverage in case of a heavily saturated and an unsaturated line are shown in Fig. 1. In the left panel of the figure we plot synthetic profiles of Ne VIII  $\lambda 770$  line (true line center optical depth  $\tau_0 = 21.0$ ) with  $N(\text{Ne VIII}) = 10^{16} \text{ cm}^{-2}$  and  $b$ -parameter of  $100 \text{ km s}^{-1}$  for  $f_c = 1.0$  (solid profile) and  $f_c = 0.8$  (dashed profile). The heavy saturation in the profile with complete coverage suggests large optical depth (i.e.  $e^{-\tau(\nu)} = 0$ ). The dashed curve showing flat bottom profile but flux level not reaching to zero, clearly suggests a partial coverage scenario with  $f_c = 1 - I(\nu)/I_0$ . Evidently, presence of only one line is sufficient to compute  $f_c$  in such a situation. In the right hand panel of Fig. 1, we show synthetic profiles of Ne VIII  $\lambda 770$  line ( $\tau_0 = 2.1$ ) with  $N = 10^{15} \text{ cm}^{-2}$  and  $b$ -parameter of  $100 \text{ km s}^{-1}$  for  $f_c = 1.0$  (solid),  $f_c = 0.8$  (short dashed) and  $f_c = 0.5$  (long dashed). For the same column density, profiles with different covering fraction look different. The line center becomes shallower for lower  $f_c$  values. The line with a column density of  $10^{15} \text{ cm}^{-2}$  will appear as  $N(\text{Ne VIII}) = 10^{14.85} \text{ cm}^{-2}$  ( $\tau_0 = 1.5$ ) and  $10^{14.60} \text{ cm}^{-2}$  ( $\tau_0 = 0.8$ ) for covering fractions of  $f_c = 0.8$  and  $0.5$  respectively. Evidently, the observed optical depth in this case is degenerate between the true optical depth and the covering fraction. Therefore, unlike the saturated case, we need at least two lines from the same ground state to estimate the true

**Table 2.** List of important Extreme-UV (EUV) lines used in this paper<sup>1</sup>.

| Ion<br>(1)          | IP(1) <sup>a</sup><br>(2) | IP(2) <sup>b</sup><br>(3) | $\lambda^c$ (Å)<br>(4) | $f_{\text{osc}}^d$<br>(5)                      | $\log T_{\text{max}}^e$<br>(6) |
|---------------------|---------------------------|---------------------------|------------------------|--|--------------------------------|
| O IV                | 54.93                     | 77.41                     | 787.7105<br>608.3968   | $1.11 \times 10^{-1}$<br>$6.70 \times 10^{-2}$ | 5.20                           |
| O V                 | 77.41                     | 113.90                    | 629.7320               | $5.15 \times 10^{-1}$                          | 5.40                           |
| N IV                | 47.45                     | 77.47                     | 765.1467               | $6.16 \times 10^{-1}$                          | 5.15                           |
| Ne V                | 97.12                     | 126.22                    | 572.3380               | $7.74 \times 10^{-2}$                          | 5.45                           |
| Ne VI               | 126.22                    | 157.93                    | 558.5940               | $9.07 \times 10^{-2}$                          | 5.65                           |
| Ne VIII             | 207.28                    | 239.10                    | 770.4089<br>780.3240   | $1.03 \times 10^{-1}$<br>$5.05 \times 10^{-2}$ | 5.85                           |
| Ar VIII             | 124.32                    | 143.45                    | 700.2450<br>713.8100   | $3.85 \times 10^{-1}$<br>$1.88 \times 10^{-1}$ | 5.75                           |
| Na IX               | 264.19                    | 299.88                    | 681.7190<br>694.1460   | $9.24 \times 10^{-2}$<br>$4.54 \times 10^{-2}$ | 5.90                           |
| Mg X                | 328.24                    | 367.54                    | 609.7930<br>624.9410   | $8.42 \times 10^{-2}$<br>$4.10 \times 10^{-2}$ | 6.05                           |
| Al XI               | 399.37                    | 442.08                    | 550.0310<br>568.1200   | $7.73 \times 10^{-2}$<br>$3.75 \times 10^{-2}$ | 6.15                           |
| Si XII <sup>†</sup> | 476.08                    | 523.52                    | 499.4060<br>520.6650   | $7.19 \times 10^{-2}$<br>$3.45 \times 10^{-2}$ | 6.35                           |

<sup>1</sup>From Verner et al. (1994)

<sup>a</sup>Creation ionization potential

<sup>b</sup>Destruction ionization potential

<sup>c</sup>Rest frame wavelength in Å

<sup>d</sup>Oscillator strength

<sup>e</sup>Temperature at which collisional ionization fraction (Sutherland & Dopita 1993) peaks

<sup>†</sup>Not covered for any of the systems reported here

column density. After estimating the covering fraction (either by flat bottom approximation or from doublet transitions) for a given species we recover the true optical depth by inverting Eq. 1. We then use the partial coverage corrected flux for Voigt profile fitting. Here we make an explicit assumption that the individual Voigt profile components in a blend all have same  $f_c$  for a given ion, but note that  $f_c$  can be strongly dependent on the velocity along the absorption trough (Srianand & Shankaranarayanan 1999; Arav et al. 1999a; Gabel et al. 2005; Arav et al. 2008). In addition inhomogeneous absorption models were shown to produce good fits for the absorption troughs as well (Arav et al. 2008; Borguet et al. 2012a). However, given the survey nature of this work and the limited  $S/N$  of the data, we deem it adequate to treat the absorber with simple covering fraction models and to reserve the use of more elaborate models for future investigations and high  $S/N$  observations.

### 4 DATA SAMPLE AND ANALYSIS

For the analysis presented in this paper, we concentrate on associated absorbers detected through Ne VIII  $\lambda 770, 780$  doublets. In Table 2 we have summarised some of the important EUV lines used in this paper including Ne VIII. Here we define, an associated absorbers as (a) those with ejection velocities  $|v_{\text{ej}}| \lesssim 8000 \text{ km s}^{-1}$  with respect to the QSO emission redshift (see e.g. Fox et al. 2008), or (b) show clear signatures of partial coverage (see e.g. Section 3) even when having higher ejection velocities (i.e.  $|v_{\text{ej}}| \geq 8000 \text{ km s}^{-1}$ ). Here, the ejection velocity  $v_{\text{ej}}$  is defined as the velocity separation between the emission redshift of the QSO and the Ne VIII optical depth weighted redshift of the absorber. The  $-v_{\text{ej}}$  sign in the ejection velocity is used whenever absorber redshift is less than the emission redshift of the QSO (i.e.  $z_{\text{abs}} \leq z_{\text{em}}$ ). How-

**Table 3.** Summary of properties of the associated Ne VIII absorbers.

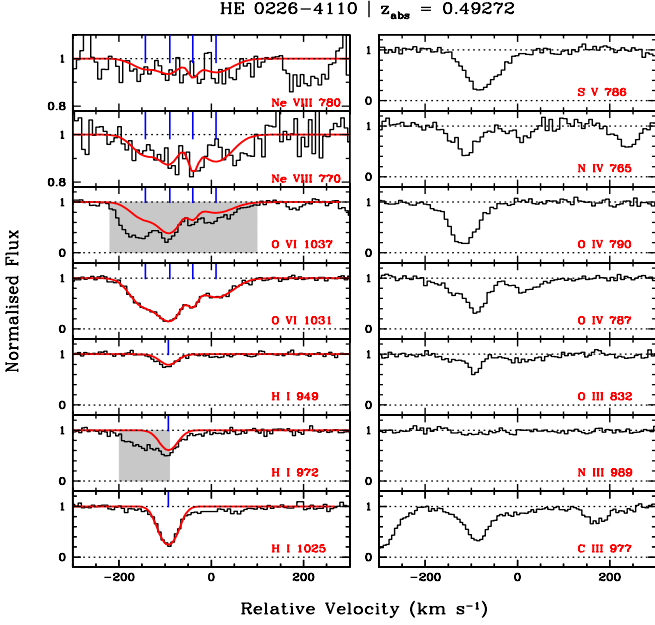
| QSO            | $z_{\text{em}}$ | $z_{\text{abs}}$ | $v_{\text{ej}}$<br>(km s <sup>-1</sup> ) | $\log L_{912\text{\AA}}$<br>(in erg s <sup>-1</sup> Hz <sup>-1</sup> ) | $\log N(\text{H I})$<br>( $N$ in cm <sup>-2</sup> ) | $\log N(\text{O VI})$<br>( $N$ in cm <sup>-2</sup> ) | $\log N(\text{Ne VIII})$<br>( $N$ in cm <sup>-2</sup> ) | $\log N(\text{Na IX})$<br>( $N$ in cm <sup>-2</sup> ) | $\log N(\text{Mg X})$<br>( $N$ in cm <sup>-2</sup> ) | Comments  | $\delta v$<br>(km s <sup>-1</sup> ) |
|----------------|-----------------|------------------|--|--|---|--|---|---|--|-----------|-------------------------------------|
| (1)            | (2)             | (3)              | (4)                                      | (5)  | (6)   | (7)  | (8)   | (9)   | (10)   | (11)      | (12)                                |
| HE 0226–4110   | 0.493           | 0.49272          | –56                                      | 31.24  | 14.49±0.01  | 14.76±0.13   | 14.09±0.19  | NA  | NA   | Secure    | 226.1                               |
| HS 1102+3441   | 0.509           | 0.48518          | –4768                                    | 30.39  | <14.52  | 15.00±0.18   | 15.22±0.20  | NA  | NA   | Secure    | 661.3                               |
| HE 0238–1904   | 0.629           | 0.59795          | –5767                                    | 31.46  | <13.71  | <13.6  | 14.22±0.03  | <14.19  | <14.82   | Tentative | 337.3                               |
|                |                 | 0.60406          | –4624                                    |  | <14.45  | 15.24±0.09   | 15.62±0.02  | <14.79  | > 15.32 <sup>1</sup>                                 | Secure    | 435.5                               |
|                |                 | 0.60989          | –3538                                    |  | <14.60  | 15.06±0.07   | 15.50±0.22  | <13.90  | > 15.11 <sup>1</sup>                                 | Secure    | 460.3                               |
| FBQS 0751+2919 | 0.916           | 0.91983          | +598                                     | 31.74  | <14.34  | NA   | 14.59±0.09  | <13.94  | BL   | Secure    | 171.0                               |
| PG 1407+265    | 0.940           | 0.93287          | –1103                                    | 31.90  | <13.71  | NA   | 14.36±0.22  | <13.60  | 14.29±0.18   | Secure    | 96.0                                |
| HB89 0107–025  | 0.956           | 0.94262          | –2057                                    | 31.16  | <14.75  | NA   | 14.27±0.04  | <13.75  | BL   | Tentative | 117.6                               |
| PG 1206+459    | 1.163           | 1.02854          | –19228                                   | 32.09  | ~14.00 <sup>2</sup>                                 | NA   | >16.11  | 15.12±0.09  | 15.59±0.08   | Secure    | 358.9                               |
| PG 1338+416    | 1.214           | 1.15456          | –8156                                    | 31.48  | <13.88  | NA   | >16.05  | 15.25±0.05  | 15.80±0.04   | Secure    | 337.9                               |
|                |                 | 1.16420          | –6818                                    |  | BL  | NA   | ~15.62  | >15.47±0.17   | ~15.47   | Secure    | 474.9                               |
|                |                 | 1.21534          | +181                                     |  | 14.04±0.04 <sup>3</sup>                             | 14.74±0.12 <sup>3</sup>                              | 14.42±0.05  | <14.18  | 14.62±0.06   | Secure    | 225.6                               |

Notes – Column 1 lists the QSO sight lines in which signatures of associated Ne VIII absorption is detected. Note that the presence of associated Ne VIII absorbers towards HE 0226–4110 and HE 0238–1904 have been reported previously by Ganguly et al. (2006) and Muzahid et al. (2012b) respectively. Column 2 lists the emission redshifts of the QSOs; Column 3 lists the Ne VIII optical depth weighted redshifts of the absorbers. Column 4 lists the ejection/outflow velocities of the Ne VIII absorbers, defined as the velocity separation between the  $z_{\text{em}}$  and  $z_{\text{abs}}$ . Column 5 lists the luminosities of the QSOs at the rest frame 912Å. Column 6,7,8,9,10 list the measurements/limits on integrated column densities of H I, O VI, Ne VIII, Na IX and Mg X respectively. During the column density estimations, effects of the partial coverage have been taken care of, whenever applicable. The species that are not available in the COS spectrum are marked by ‘NA’. The species that are heavily blended are marked by ‘BL’. Column 11 tells us whether the Ne VIII detection is secure. Column 12 lists the line spreads of Ne VIII absorption. To compute the line spread we followed the procedure as described in (Muzahid et al. 2012a, see their Fig. 3).

<sup>1</sup> Detected in *FUSE*

<sup>2</sup> Detected in *HST*/STIS (E230M)

<sup>3</sup> Detected in *HST*/FOS (G270H)



**Figure 2.** Velocity plot of the associated Ne VIII absorption system at  $z_{\text{abs}} = 0.49272$  towards HE 0226–4110. The zero velocity corresponds to the emission redshift ( $z_{\text{em}} = 0.493$ ) of the QSO. In case of H I, O VI and Ne VIII, the smooth curves are the best fitting Voigt profiles, overlaid on top of the data. The vertical ticks mark the centroids of the individual Voigt profile components. Absorption features unrelated to this system are marked by the shaded regions.

ever, in subsequent discussions we will use the term “higher velocity” assuming modulus of the ejection velocity.

We have searched for the Ne VIII doublets in the relevant spectral range by imposing the doublet matching criteria. For each identified coincidences we checked the consistency of the profile shape. However, we do not impose the condition of optical depth ratio consistency for the Ne VIII doublets, keeping in mind the effects of partial coverage as discussed in Section 3. We then checked for the presence of all other species at the redshift of the identified Ne VIII doublets. We find the signatures of associated Ne VIII absorption only in 8 out of 20 (40%) lines of sight. We have detected 12 associated Ne VIII absorption systems in total towards 8 lines of sight. Note that any continuous absorption comprised of single/multiple component(s) are treated as system. Apart from the system detected towards PG 1206+459, all other systems are detected within  $\sim 8000 \text{ km s}^{-1}$  with respect to the QSOs. Because of clear signature of partial coverage in the Ne VIII doublet we have included the system in our sample. Based on the number per unit redshift of Ne VIII absorbers (Narayanan et al. 2009) we expect to detect only 2 Ne VIII absorbers from the intervening gas. Interestingly none of these Ne VIII absorption detected is towards the 7 radio bright QSOs. Although we search up to  $8000 \text{ km s}^{-1}$ , 67 per cent of the absorbers are detected within  $5000 \text{ km s}^{-1}$  from the emission redshift of the QSO.

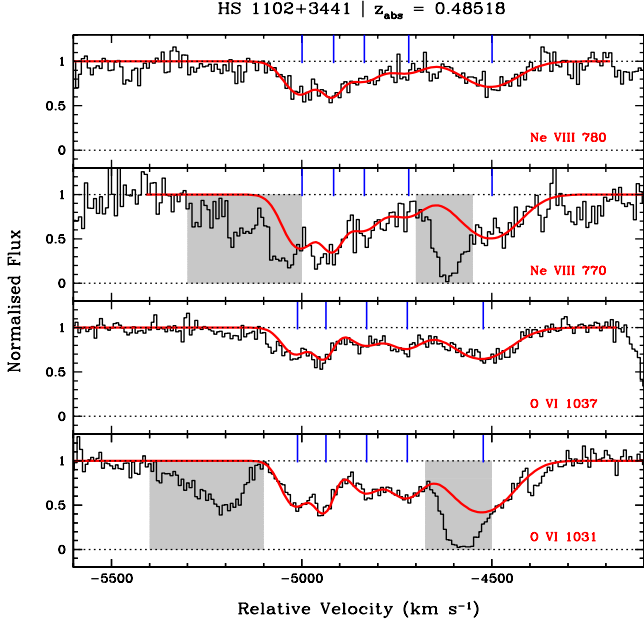
Details of the sight lines and the Ne VIII absorbers are summarized in Table 3. Apart for  $z_{\text{abs}} = 0.94262$  towards HB89 0107–025 (marked as “Tentative” in column #11 of Table 3), all other associated system in our sample show at least one other species which indeed makes our Ne VIII identification robust. Next, we provide details of each individual Ne VIII systems detected in our sample.

#### 4.1 $z_{\text{abs}} = 0.49272$ towards HE 0226–4110

The ejection velocity of the absorber is only  $\sim -56 \text{ km s}^{-1}$ . The velocity plot of this system clearly shows that the Ne VIII absorption is spread over  $\sim 226 \text{ km s}^{-1}$  (see Fig. 2). However, as Ne VIII doublets occur in the extreme blue end of the COS spectrum, the  $S/N$  is not high. A tentative detection of Ne VIII in this system in the *FUSE* data was reported earlier by Ganguly et al. (2006). Here we confirm their detection. Apart from the weak Ne VIII, other ions detected in the COS spectrum are C III, O III, N IV, O IV, O VI and possibly S V. The detection of O V is also reported in the *FUSE* spectrum by Ganguly et al. (2006) which is not covered by the COS spectrum. As the O VI  $\lambda 1037$  line is severely blended (see Fig. 2), we could not use O VI doublets to estimate the O VI covering fraction. Ne VIII, on the other hand, is very weak. Na IX and Mg X doublets as well as Ly  $\alpha$  line are not covered by the COS spectrum. Nevertheless, unblended profiles of Ly  $\beta$  and Ly  $\delta$  transitions are found to be consistent with covering fraction ( $f_c$ ) being 1.0, suggesting complete occultation of the background source by the absorber. The measured column density is  $\log N(\text{H I}) [\text{cm}^{-2}] = 14.49 \pm 0.01$ . The unblended O VI  $\lambda 1031$  profile is fitted with four Voigt profile components. The total column density (i.e. the summed up column densities measured in four components) is  $\log N(\text{O VI}) [\text{cm}^{-2}] = 14.76 \pm 0.13$ . Because of the low  $S/N$  ratio we use the component structure of O VI absorption to fit the Ne VIII doublets keeping the  $b$ -parameter tied with the corresponding O VI component. The estimated total column densities of Ne VIII is  $\log N(\text{Ne VIII}) [\text{cm}^{-2}] = 14.09 \pm 0.19$ . The total column densities for Ne VIII and O VI as reported by Ganguly et al. (2006), using apparent optical depth technique, (i.e.  $\log N(\text{Ne VIII}) [\text{cm}^{-2}] = 14.25 \pm 0.15$  and  $\log N(\text{O VI}) [\text{cm}^{-2}] = 14.84 \pm 0.08$ ) are very similar to our measurements. The difference in profile between high ions (e.g. O VI, Ne VIII) and low ions (e.g. H I, C III, O III, etc.) is clearly evident from the system plot. Only the strongest O VI component is accompanied by these low ions. Such a difference in profiles possibly suggests multiphase nature of the absorbing gas. A detailed discussion on the absorbing system and the QSO properties can be found in Ganguly et al. (2006), therefore we do not discuss this system in detail.

#### 4.2 $z_{\text{abs}} = 0.48518$ towards HS 1102+3441

The ejection velocity of this system is  $v_{\text{ej}} \sim -4768 \text{ km s}^{-1}$  and is detected through O VI and Ne VIII absorption, kinematically spread over  $\sim 700 \text{ km s}^{-1}$  (see Fig. 3). The Ne VIII  $\lambda 770$  is blended with unknown contaminants whereas O VI  $\lambda 1031$  is found to be blended with Ly  $\alpha$  absorption of  $z_{\text{abs}} = 0.26165$  system. Unblended profiles of Ne VIII  $\lambda 780$  and O VI  $\lambda 1037$  clearly show multicomponent structures with at least five components contributing to the absorption. Because of the blending we do not attempt to estimate the covering fraction for either of the detected ions. The Voigt profile fitting assuming complete coverage seems to give reasonably good fit to the unaffected pixels of the blended profiles. The estimated total column densities are  $\log N(\text{O VI}) [\text{cm}^{-2}] = 15.00 \pm 0.18$  and  $\log N(\text{Ne VIII}) [\text{cm}^{-2}] = 15.22 \pm 0.20$ . Ly  $\alpha$  is not covered by the COS spectrum. Ly  $\beta$  and Ly  $\gamma$  lines are contaminated. Nevertheless, we use the contaminated Ly  $\beta$  profile to put an upper limit on  $N(\text{H I})$ . Assuming component structure and  $b$ -parameters similar to Ne VIII, we find  $N(\text{H I}) < 10^{14.52} \text{ cm}^{-2}$ .



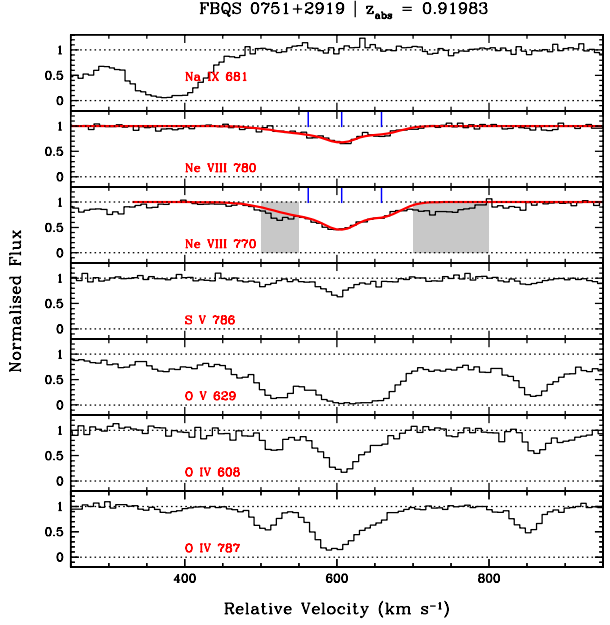
**Figure 3.** Velocity plot of the associated Ne VIII absorption system at  $z_{\text{abs}} = 0.48518$  towards HS 1102+3441. The zero velocity corresponds to the emission redshift ( $z_{\text{em}} = 0.509$ ) of the QSO. The smooth curves overplotted on top of the data are the best fitting Voigt profiles. The vertical ticks mark the centroids of the individual Voigt profile components. Absorption features unrelated to this absorber are marked by the shaded regions.

#### 4.3 $z_{\text{abs}} = 0.59795, 0.60406$ & $0.60989$ towards HE 0238–1904

These systems are detected at  $v_{\text{ej}} \sim -4500 \text{ km s}^{-1}$  away from the emission redshift of the QSO, in seven absorption components kinematically spread over  $\sim 1800 \text{ km s}^{-1}$ . We have presented a detailed analysis of this absorber in an earlier paper (see Muzahid et al. 2012b). Mg X lines from this system are severely affected by the Galactic  $\text{H}_2$  absorption and we were able to measure  $N(\text{Mg X})$  only in some of the components showing Ne VIII detection. The Na IX doublets are not covered by the COS spectrum for this system. We looked at *FUSE* LiF2a data covering the Na IX doublets but do not find any clear signature of Na IX absorption.

#### 4.4 $z_{\text{abs}} = 0.91983$ towards FBQS 0751+2919

The ejection velocity of this system is  $v_{\text{ej}} \sim +598 \text{ km s}^{-1}$ , suggesting  $z_{\text{abs}} > z_{\text{em}}$ . Ne VIII doublets in this system clearly show multicomponent structure spreads over  $\sim 170 \text{ km s}^{-1}$  (see Fig. 4). Apart from Ne VIII, other ions detected in this system are O IV, O V and S V. Ne VIII  $\lambda 770$  seems to be mildly blended in both the wings. The optical depth ratios in the core pixels of Ne VIII absorption are consistent with  $f_c = 1.0$ . The Voigt profile fitting of the Ne VIII doublets leads to a total column density of  $\log N(\text{Ne VIII})[\text{cm}^{-2}] = 14.59 \pm 0.09$ . For this system O VI lines are not covered by the COS spectrum. The clear non-detection of Na IX  $\lambda 681$  transition is consistent with  $\log N(\text{Na IX})[\text{cm}^{-2}] < 13.94$  at  $3\sigma$  confidence level. The expected positions of both the members of Mg X doublet are heavily blended and hence we do not have any estimate on  $N(\text{Mg X})$ . Very high order Lyman series lines (i.e. with  $\lambda_{\text{rest}} < 930 \text{ \AA}$ ) are covered by the COS spectrum where we do not find any clear signature of H I absorption. Non-detection of Ly-9 transition is consistent with  $N(\text{H I}) < 10^{14.34} \text{ cm}^{-2}$ .



**Figure 4.** Velocity plot of the associated Ne VIII absorption system at  $z_{\text{abs}} = 0.91983$  towards FBQS 0751+2919. The zero velocity corresponds to the emission redshift ( $z_{\text{em}} = 0.915$ ) of the QSO. The smooth curves overplotted on top of the data in the Ne VIII panel are the best fitting Voigt profiles. The vertical ticks mark the centroids of the individual Voigt profile components.

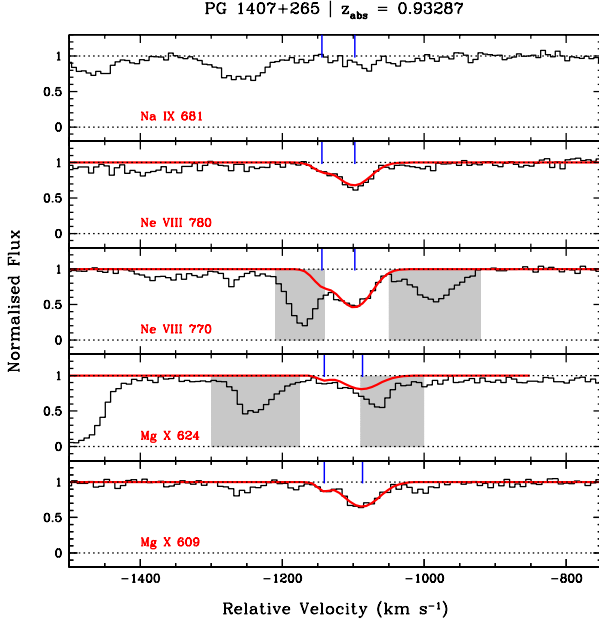
#### 4.5 $z_{\text{abs}} = 0.93287$ towards PG 1407+265

The ejection velocity of this system is  $v_{\text{ej}} \sim -1103 \text{ km s}^{-1}$ . Ne VIII absorption has two components spread over  $\sim 100 \text{ km s}^{-1}$  (see Fig. 5). Ne VIII  $\lambda 770$  line is found to be contaminated in both the wings. Nevertheless, the unblended core pixels are consistent with covering fraction  $f_c = 1.0$ . We estimate  $\log N(\text{Ne VIII})[\text{cm}^{-2}] = 14.36 \pm 0.22$ . Mg X doublet is fitted with two components slightly off-centered with respect to the Ne VIII components. Estimated total column density of Mg X absorption is  $\log N(\text{Mg X})[\text{cm}^{-2}] = 14.29 \pm 0.18$ . The non-detection of Na IX  $\lambda 681$  transition is consistent with  $\log N(\text{Na IX})[\text{cm}^{-2}] < 13.60$  at  $3\sigma$  confidence level. O VI doublets are not covered by the COS spectrum. Very high order Lyman series lines (i.e. with  $\lambda_{\text{rest}} < 930 \text{ \AA}$ ) are covered by the COS spectrum where we do not find any clear signature of H I absorption. In addition, no convincing Ly $\beta$  (or Ly $\gamma$ ) absorption is seen in archival *HST*/FOS spectrum, obtained with the G190H grating. We note that the non-detection of Ly $\beta$  is consistent with  $N(\text{H I}) < 10^{13.71} \text{ cm}^{-2}$ .

#### 4.6 $z_{\text{abs}} = 0.94262$ towards HB89 0107–025

The ejection velocity of this system is  $v_{\text{ej}} \sim -2057 \text{ km s}^{-1}$  and is detected only through Ne VIII absorption spread over  $\sim 120 \text{ km s}^{-1}$  (see Fig. 6). The covering fraction of Ne VIII is consistent with  $f_c = 1$  within the continuum placement uncertainty. We measure  $\log N(\text{Ne VIII})[\text{cm}^{-2}] = 14.27 \pm 0.04$ , whereas the non-detection of Na IX  $\lambda 681$  transition in the COS spectrum is consistent with  $N(\text{Na IX}) < 10^{13.75} \text{ cm}^{-2}$  at  $3\sigma$  confidence level. The expected positions of Mg X doublets are contaminated and thus we cannot confirm its presence. In addition, we do not detect any other ion in the COS spectrum, corresponding to this system. O VI is not covered by COS and we do not find any signature of O VI lines in



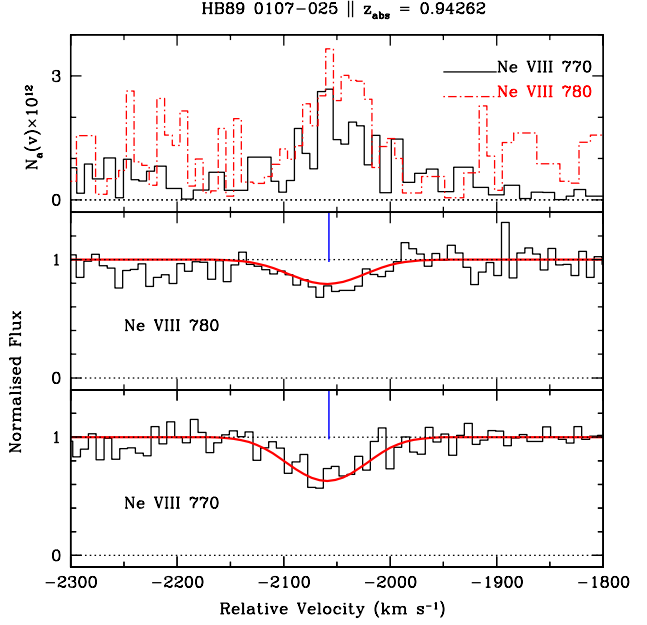


**Figure 5.** Velocity plot of the associated Ne VIII absorption system at  $z_{\text{abs}} = 0.93287$  towards PG 1407+265. The zero velocity corresponds to the emission redshift ( $z_{\text{em}} = 0.940$ ) of the QSO. The smooth curves overplotted on top of the data are the best fitting Voigt profiles. The vertical tick marks the centroids of the individual Voigt profile components.

the FOS/G190H spectra. Therefore, we treat this system as tentative one. The non-detection of Ly $\beta$  in FOS/190H spectra is consistent with  $N(\text{H I}) < 10^{14.75} \text{ cm}^{-2}$ .

#### 4.7 $z_{\text{abs}} = 1.02854$ towards PG 1206+459

This is the highest ejection velocity associated system detected in our sample, with  $v_{\text{ej}} \sim -19,228 \text{ km s}^{-1}$ , and Ne VIII absorption is spread over  $\sim 360 \text{ km s}^{-1}$ . This system is part of our sample, despite having large ejection velocity, as it shows clear signature of partial coverage. In Fig. 7 we show absorption profiles of different species as a function of their outflow velocity with respect to the QSO emission redshift ( $z_{\text{em}} = 1.214$ ). The highly ionized species like Ar VIII  $\lambda\lambda 700,713$ ; Ne VIII  $\lambda\lambda 770,780$ ; Na IX  $\lambda\lambda 681,694$  and Mg X  $\lambda\lambda 609,624$ , originating from this absorber are detected in the COS spectrum. In addition, we also detect species like O IV, O V, N IV in COS and H I, and N V in the *HST*/STIS E230M spectrum. The STIS spectrum does not cover Ly $\beta$ , C III or C IV lines. However, expected wavelength range of Si IV, Si III  $\lambda 1206$ , Si II  $\lambda 1260$  and C II  $\lambda 1334$  lines are covered in the STIS data, but we do not detect any of these species. The profiles of O IV, N IV, N V and Ne VIII doublets are flat over  $\sim 300 \text{ km s}^{-1}$ , indicating partial coverage and heavy saturation of these lines. The flat bottom assumption (see Section 3) gives the covering fractions for O IV, N IV, N V, and Ne VIII as  $f_c = 0.21, 0.40, 0.32$  and  $0.59$  respectively. Unlike these species, the doublets of Mg X absorption are unsaturated. The uncontaminated profile of Mg X  $\lambda 609$  clearly shows component structure with at least two components contributing to the absorption. For the subsequent discussions on this system (see section 5.1) we will refer the higher and lower velocity components (i.e. blue and red) as component-1 and component-2 respectively. The blue wing of the Mg X  $\lambda 624$  is blended with S IV  $\lambda 657$  line from  $z_{\text{abs}} = 0.9275$ . The core pixels of Mg X  $\lambda 624$  which are not



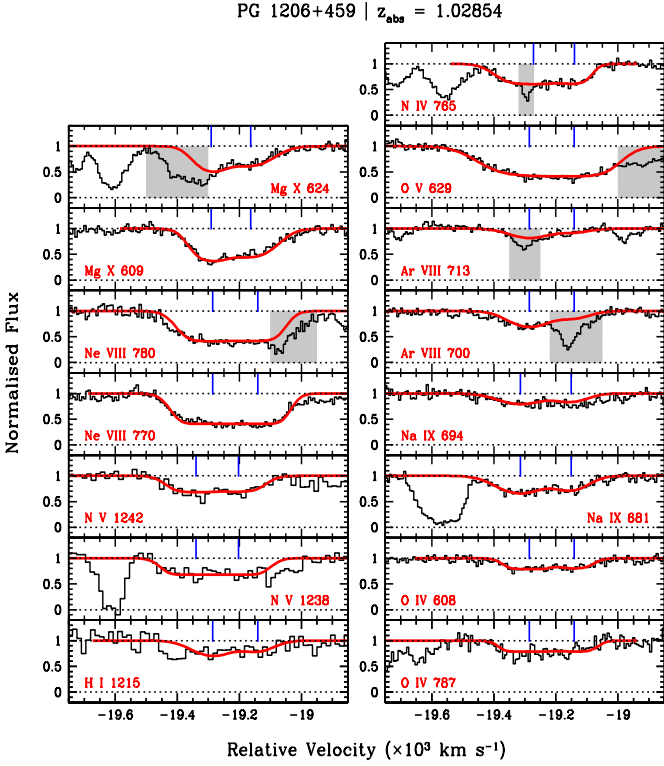
**Figure 6.** Velocity plot of the associated Ne VIII absorber at  $z_{\text{abs}} = 0.94262$  towards HB89 0107-025. The zero velocity corresponds to the emission redshift ( $z_{\text{em}} = 0.956$ ) of the QSO. The smooth curves overplotted on top of the data are the best fitting Voigt profiles. The vertical tick marks the line centroid. The apparent column density profiles of Ne VIII doublets [in units of  $10^{12} \text{ cm}^{-2}(\text{km s}^{-1})^{-1}$ ] are plotted in the top panel.

affected by this blending are consistent with  $f_c = 0.68$ . For the singlet transition of O V, we have taken  $f_c = 0.59$  which seems to be consistent with (nearly) flat bottom seen in the profile. We note that, O V profile is unusually broad which could possibly due to unknown contamination. Therefore, the actual  $f_c$  for O V could be even less. Because of the weak line strength we do not attempt to estimate  $f_c$  for Na IX, instead we use Ne VIII covering fraction for fitting. We note that unlike Ne VIII, profiles of Na IX are not saturated.

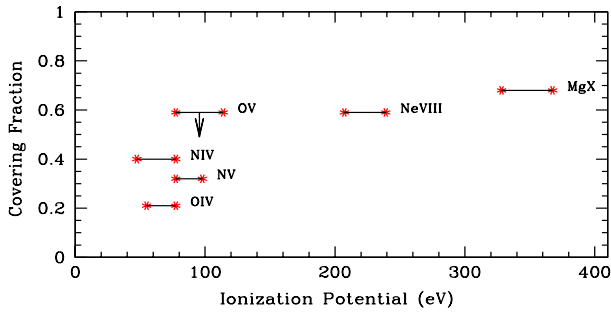
In Fig. 8, we have plotted the covering fractions ( $f_c$ ) of different species detected in this system as a function of ionization potentials. It is clear from the figure that we have two sets of covering fractions for this system. The species with high ionization potentials (i.e. Ne VIII, Mg X) are showing covering fraction  $f_c \gtrsim 0.6$ , whereas, the low ionization species (i.e. O IV, N IV, N V) show  $f_c \lesssim 0.4$ . Ionization potential dependent covering fraction have already been reported by Telfer et al. (1998); Muzahid et al. (2012b), where, the idea of multiphase structure of the absorbing gas has been put forward, with different species having different projected area. In view of this, the covering fraction of Na IX should be similar to that of Ne VIII, as they have ionization potentials of the same order. This also justifies our use of Ne VIII covering fraction for the fitting of Na IX doublets. Such an assumption indeed gives good fit to Na IX doublets.

Parameters estimated through Voigt profile fitting after correcting for partial coverage are given in Table 4. We treat column densities of all the species as lower limits in the case of ions showing flat bottom profiles. We note that, both the members of Ar VIII doublets are partially blended by unknown contaminants which made the covering fraction estimation impossible. However, since the ionization potentials (creation+destruction) of Ar VIII are com-





**Figure 7.** Velocity plot of the associated Ne VIII absorption system at  $z_{\text{abs}} = 1.02854$  towards PG 1206+459. The zero velocity corresponds to the emission redshift ( $z_{\text{em}} = 1.163$ ) of the QSO. The smooth curves overplotted on top of the data are the best fitting Voigt profiles after correcting for the effect of partial coverage. The vertical ticks mark the centroids of the individual Voigt profile components. Ly $\alpha$  and N V are from STIS E230M spectrum. Absorption lines unrelated to this system are marked by the shaded regions.



**Figure 8.** Covering fractions of different species detected in  $z_{\text{abs}} = 1.02854$  towards PG 1206+459 as a function of ionization potential. The energy range between the creation and destruction ionization potentials of a given species are shown by the two stars connected by a solid line.

parable to those of O V, we take  $f_c = 0.59$ . We note that, because of blend  $N(\text{Ar VIII})$  should be taken as upper limit.

At the expected position of O VI, some absorption is seen in the low resolution *HST*/FOS G190H spectrum. However, due to severe blending in both members of the doublets, we do not attempt to estimate the covering fraction. Estimated conservative upper limit on O VI column density is  $\log N(\text{O VI}) [\text{cm}^{-2}] < 14.80$ , assuming  $f_c = 0.59$ . In addition, we do not detect any clear signature of Ly $\beta$  absorption in G190H spectrum. Weak Ly $\alpha$  absorption

**Table 4.** Partial coverage corrected Voigt profile fit parameters for the absorber at  $z_{\text{abs}} = 1.02854$  towards PG 1206+459.

| $v_{\text{ej}} (\text{km s}^{-1})$ | Ion     | $b (\text{km s}^{-1})$ | $\log N (\text{cm}^{-2})$ | $f_c$              |
|------------------------------------|---------|------------------------|---------------------------|--------------------|
| (1)                                | (2)     | (3)                    | (4)                       | (5)                |
| -19290                             | Mg X    | $65 \pm 4$             | $15.31 \pm 0.06$          | 0.68 ( <i>db</i> ) |
| -19314                             | Na IX   | $93 \pm 12$            | $14.93 \pm 0.05$          | 0.59 ( <i>aa</i> ) |
| -19285                             | Ne VIII | $83 \pm 4$             | $> 15.90 \pm 0.06$        | 0.59 ( <i>fb</i> ) |
| -19285                             | Ar VIII | $83 \pm 0$             | $< 14.19 \pm 0.02$        | 0.59 ( <i>aa</i> ) |
| -19285                             | O V     | $141 \pm 5$            | $> 14.92 \pm 0.03$        | 0.59 ( <i>fb</i> ) |
| -19339                             | N V     | $72 \pm 18$            | $> 15.38 \pm 0.40$        | 0.32 ( <i>fb</i> ) |
| -19285                             | O IV    | $57 \pm 11$            | $> 15.85 \pm 0.23$        | 0.21 ( <i>fb</i> ) |
| -19272                             | N IV    | $94 \pm 17$            | $> 14.77 \pm 0.18$        | 0.40 ( <i>fb</i> ) |
| -19285                             | H I     | $83 \pm 0$             | $\sim 13.78$              | 0.59 ( <i>aa</i> ) |
| -19285                             | H I     | $83 \pm 0$             | $\sim 14.42$              | 0.30 ( <i>aa</i> ) |
| -19163                             | Mg X    | $88 \pm 9$             | $15.28 \pm 0.06$          | 0.68 ( <i>db</i> ) |
| -19150                             | Na IX   | $70 \pm 11$            | $14.68 \pm 0.08$          | 0.59 ( <i>aa</i> ) |
| -19140                             | Ne VIII | $68 \pm 5$             | $> 15.69 \pm 0.11$        | 0.59 ( <i>fb</i> ) |
| -19140                             | Ar VIII | $68 \pm 0$             | $< 13.66 \pm 0.07$        | 0.59 ( <i>aa</i> ) |
| -19140                             | O V     | $113 \pm 11$           | $> 14.97 \pm 0.05$        | 0.59 ( <i>fb</i> ) |
| -19202                             | N V     | $70 \pm 26$            | $> 15.21 \pm 0.38$        | 0.32 ( <i>fb</i> ) |
| -19140                             | O IV    | $53 \pm 12$            | $> 15.40 \pm 0.13$        | 0.21 ( <i>fb</i> ) |
| -19140                             | N IV    | $46 \pm 15$            | $> 14.28 \pm 0.36$        | 0.40 ( <i>fb</i> ) |
| -19140                             | H I     | $68 \pm 0$             | $\sim 13.61$              | 0.59 ( <i>aa</i> ) |
| -19140                             | H I     | $68 \pm 0$             | $\sim 14.01$              | 0.30 ( <i>aa</i> ) |

Note – Listed errors on all the quantities in this paper only include the statistical errors. For  $v_{\text{ej}}$  the COS calibration uncertainty is  $\sim \pm 10 \text{ km s}^{-1}$ . In addition, the uncertainty in the COS LSF introduces errors of at least 1 to 3  $\text{km s}^{-1}$  in these profile fit line widths. Zero error implies that the parameter was tied/fixed during fitting. Covering fraction,  $f_c$  used to estimate the column density is given in column 5. Method used to compute  $f_c$  is mentioned in parenthesis. “*fb*” – from flat bottom profile, “*db*” – from doublets, “*aa*” – physically motivated assumed value. Note that the column density estimated from the flat bottom profile (i.e. “*fb*”) should be taken as lower limit.

line, seen in STIS/E230M spectrum, is fitted with two different values of covering fractions (i.e.  $f_c = 0.59$  and 0.30; see Table 4), in order to estimate the maximum H I content associated with the high and low ionization phases. However, in both the phases  $N(\text{H I})$  found to be  $< 10^{14.5} \text{ cm}^{-2}$ . All these suggest a very little neutral hydrogen content in this absorber.

#### 4.8 $z_{\text{abs}} = 1.21534$ towards PG 1338+416

The ejection velocity of this system is  $v_{\text{ej}} \sim +181 \text{ km s}^{-1}$  suggesting  $z_{\text{abs}} > z_{\text{em}}$ . This absorber (see the rightmost panel of Fig. 9) is primarily detected through the presence of O VI doublets in FOS/G270H spectrum and subsequently confirmed with various other low ionization species (e.g. O III, N IV, O IV, O V etc.) in COS spectrum. Weak absorption from high ionization species like Mg X and Ne VIII are also detected. However, Ne VIII  $\lambda 780$  profile is blended with strong Ly $\beta$  absorption from  $z_{\text{abs}} = 0.6863$  system. The Mg X  $\lambda 609$  line is heavily blended, possibly with low redshift Ly $\alpha$  line and hence not shown in the figure. The non-detection of Na IX  $\lambda 681$  is consistent with  $\log N(\text{Na IX}) [\text{cm}^{-2}] < 14.18$  at  $3\sigma$  confidence level. O IV  $\lambda 608$  line is severely blended with Mg X  $\lambda 624$  line from  $z_{\text{abs}} = 1.15456$ . O III  $\lambda 702$  line is partially blended with unknown contaminants. The uncontaminated low ionization species (i.e. N IV  $\lambda 765$ , O IV  $\lambda 787$ ) clearly show multicomponent structure. In both cases, at least two Voigt profile components (shown by vertical dashed lines) are required to get best fitted  $\chi^2$  close to 1. Unlike low ionization species, Ne VIII  $\lambda 780$  absorption shows smooth and/or broad profile which is well fitted by a

**Table 5.** Voigt profile fit parameters for the absorber at  $z_{\text{abs}} = 1.21534$  towards PG 1338+416 using  $f_c = 1$  for all the species.

| $v_{\text{ej}}(\text{km s}^{-1})$ | Ion     | $b(\text{km s}^{-1})$ | $\log N(\text{cm}^{-2})$ |
|-----------------------------------|---------|-----------------------|--------------------------|
| (1)                               | (2)     | (3)                   | (4)                      |
| +81                               | H I     | $137 \pm 14$          | $14.04 \pm 0.04$         |
| +101                              | N V     | $144 \pm 15$          | $14.36 \pm 0.04$         |
| +121                              | O VI    | $158 \pm 49$          | $14.74 \pm 0.12$         |
| +126                              | N IV    | $44 \pm 2$            | $14.25 \pm 0.03$         |
| +126                              | O IV    | $44 \pm 2$            | $15.08 \pm 0.03$         |
| +126                              | O III   | $44 \pm 0$            | $14.82 \pm 0.01$         |
| +136                              | O V     | $45 \pm 3$            | $14.78 \pm 0.05$         |
| +139                              | C III   | $105 \pm 17$          | $13.91 \pm 0.06$         |
| +181                              | Ne VIII | $91 \pm 12$           | $14.42 \pm 0.05$         |
| +181                              | Mg X    | $91 \pm 0$            | $14.62 \pm 0.06$         |
| +214                              | N IV    | $40 \pm 5$            | $13.80 \pm 0.06$         |
| +214                              | O IV    | $40 \pm 5$            | $14.53 \pm 0.07$         |
| +214                              | O III   | $40 \pm 0$            | $14.26 \pm 0.03$         |
| +223                              | O V     | $32 \pm 3$            | $14.55 \pm 0.06$         |

single component. Due to poor spectral resolution, all the ions detected in FOS can be fitted with a single component.

We do not find a clear signature of partial coverage in any line. For example, N V and O VI doublets are well fitted with  $f_c = 1.0$  and do not show non-zero flat bottom profiles. The Ly $\alpha$  and (weak) Ly $\beta$  absorption are also consistent with complete coverage of the background source by the absorber. The Voigt profile fit parameters for this absorber are given in Table 5. We would like to mention here that, because of blending in O III line and saturation in O V line,  $N(\text{O III})$  and  $N(\text{O V})$  should be taken as upper and lower limits respectively. We will use these bounds in section 5.3, where we discuss the photoionization modelling of this system. In passing, we note that H I and O VI line centroids are offset by  $\sim 40 \text{ km s}^{-1}$ . This could be a signature of multiphase gas. We also note that, H I and C III line centroids are offset by  $\sim 60 \text{ km s}^{-1}$ . However, as they are detected in spectra taken with two different instruments (i.e. FOS G270H and G190H), such an offset could also be attributed to the systematic uncertainties.

#### 4.9 $z_{\text{abs}} = 1.16420$ towards PG 1338+416

The ejection velocity of this system is  $v_{\text{ej}} \sim -6818 \text{ km s}^{-1}$ . The velocity plot of this systems is shown in the middle panel of Fig. 9. Apart from O V and Na IX  $\lambda 681$ , all other detected ions in this system show complex blend in their profiles. The overall similarity in profiles of various ions clearly assures their presence. We do not find any other contamination in Na IX  $\lambda 681$  absorption and it shows very similar profile like O V. Therefore, we believe Na IX detection is robust, although the blue wing of Na IX  $\lambda 694$  line is severely blended. Ne VI  $\lambda 558$  absorption falls near the Galactic Ly $\alpha$  absorption and hence the continuum around this absorption is not well constrained. Since O V is singlet transition and Na IX  $\lambda 694$  is blended, we did not estimate covering fraction for any of these ions. We assume  $f_c = 1$  to get a lower limit on column densities. At least four Voigt profile components are required to fit the unblended O V and Na IX  $\lambda 681$  profiles. The Na IX to O V column density ratio in all four components are consistent within factor  $\sim 2$  (e.g.  $\log N(\text{Na IX})/N(\text{O V}) = 0.27 \pm 0.21$ ). Because of contamination in the case of Mg X and Ne VIII lines and poorly constrained continuum in the case of Ne VI  $\lambda 558$  line we do not perform Voigt profile fitting for these absorption. Instead, we check the consistency of synthetic profiles generated using the component struc-

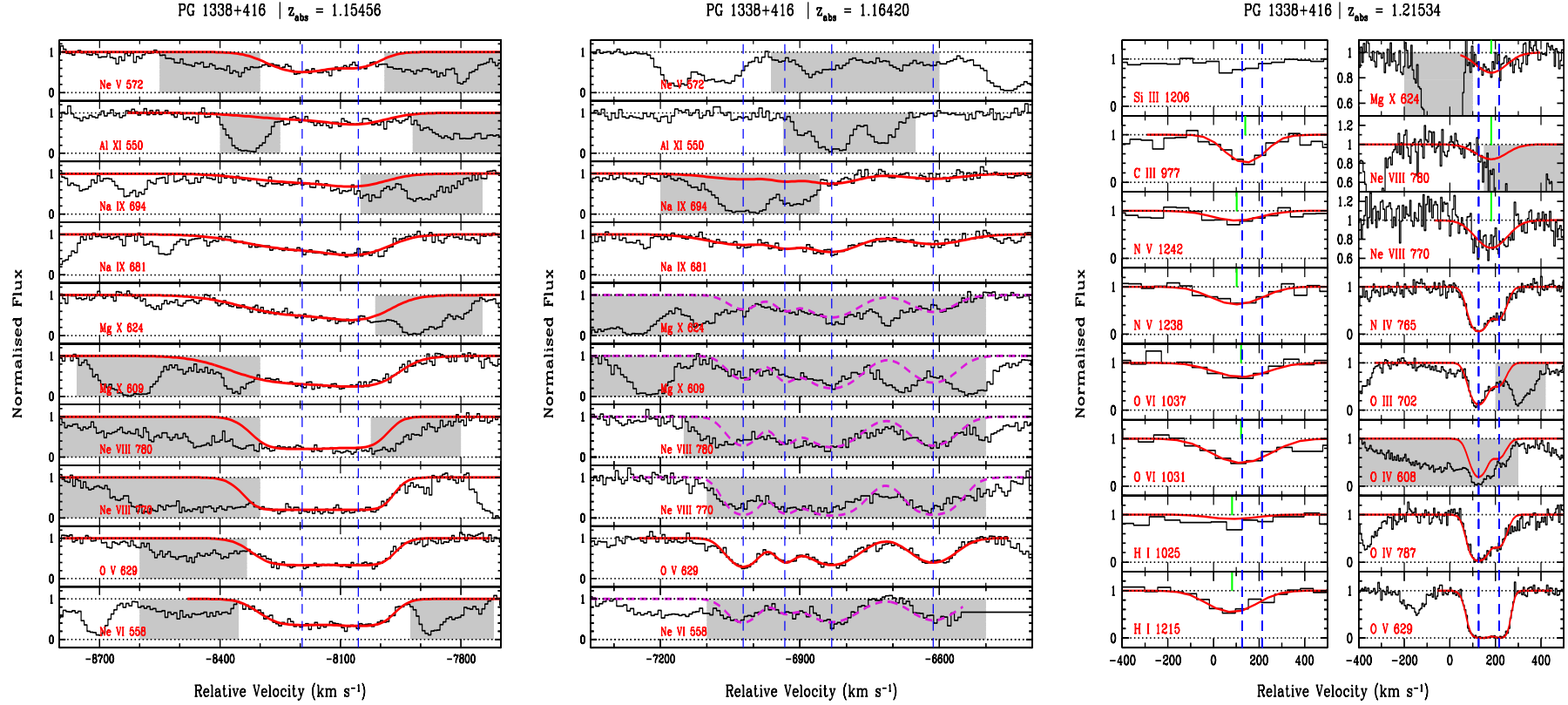
**Table 6.** Voigt profile fit parameters for  $z_{\text{abs}} = 1.16420$  towards PG 1338+416 assuming  $f_c = 1$  for all the species.

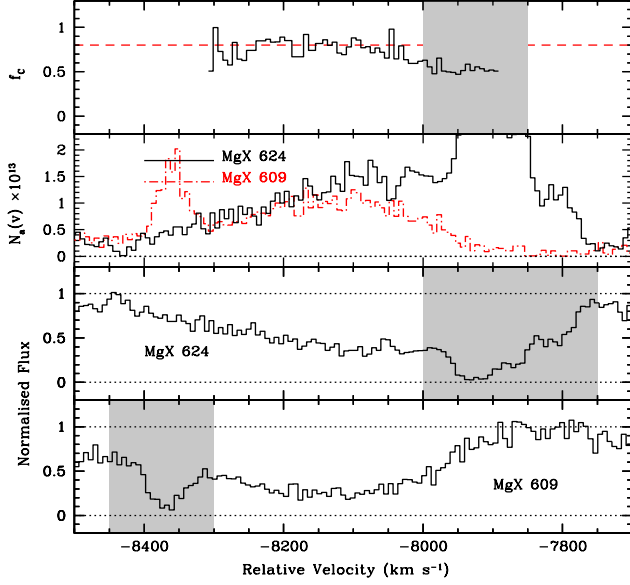
| $v_{\text{ej}}(\text{km s}^{-1})$ | Ion     | $b(\text{km s}^{-1})$ | $\log N(\text{cm}^{-2})$ |
|-----------------------------------|---------|-----------------------|--------------------------|
| (1)                               | (2)     | (3)                   | (4)                      |
| -7022                             | Na IX   | $100 \pm 13$          | $> 14.50 \pm 0.05$       |
|                                   | O V     | $40 \pm 3$            | $> 14.03 \pm 0.02$       |
|                                   | Mg X    | 40                    | $\sim 14.67$             |
|                                   | Ne VIII | 40                    | $\sim 14.94$             |
| -6932                             | Ne VI   | 40                    | $\sim 14.68$             |
|                                   | Na IX   | $34 \pm 11$           | $> 13.91 \pm 0.15$       |
|                                   | O V     | $27 \pm 4$            | $> 13.68 \pm 0.07$       |
|                                   | Mg X    | 27                    | $\sim 14.67$             |
| -6832                             | Ne VIII | 27                    | $\sim 14.50$             |
|                                   | Ne VI   | 27                    | $\sim 14.14$             |
|                                   | Na IX   | $74 \pm 7$            | $> 14.65 \pm 0.04$       |
|                                   | O V     | $66 \pm 4$            | $> 14.17 \pm 0.02$       |
| -6613                             | Mg X    | 66                    | $\sim 15.20$             |
|                                   | Ne VIII | 66                    | $\sim 15.14$             |
|                                   | Ne VI   | 66                    | $\sim 14.87$             |
|                                   | Na IX   | $86 \pm 14$           | $> 14.40 \pm 0.06$       |
| -6613                             | O V     | $57 \pm 3$            | $> 14.04 \pm 0.02$       |
|                                   | Mg X    | 57                    | $\sim 15.09$             |
|                                   | Ne VIII | 57                    | $\sim 14.91$             |
|                                   | Ne VI   | 57                    | $\sim 14.75$             |

ture and the  $b$ -parameters similar to O V line, assuming  $f_c = 1.0$ . The synthetic profiles are shown in smooth dashed curves on top of data, in the middle panel of Fig. 9. The highest optical depth pixels in Ne VIII doublets are roughly consistent with  $f_c \gtrsim 0.8$ . The line measurements for this system are presented in Table 6. The low resolution FOS/G190H spectrum shows absorption in the expected position of O VI. However, contamination of O VI lines from  $z_{\text{abs}} = 1.15456$  absorber do not allow any reliable column density estimation. Ly $\alpha$  and Ly $\beta$  absorption from this absorber are covered by the G270H and G190H spectra respectively. However, Ly $\beta$  is found to be stronger than Ly $\alpha$ , suggesting a possible contamination in Ly $\beta$ . Ly $\alpha$ , on the other hand, is contaminated with Galactic Fe II lines. Therefore, we do not present any measurement for H I in Table 6. Due to poorly constrained  $f_c$ , the column density measurements are highly uncertain and hence we do not discuss the ionization modelling for this system, in spite of the presence of Na IX.

#### 4.10 $z_{\text{abs}} = 1.15456$ towards PG 1338+416

The ejection velocity of this system is  $v_{\text{ej}} \sim -8156 \text{ km s}^{-1}$ , with Ne VIII absorption spread over  $\sim 340 \text{ km s}^{-1}$ . The profiles of different species originating from this system are plotted as a function of outflow velocity in the leftmost panel of Fig. 9. This is the highest Mg X column density system in our sample. The core pixels of Mg X doublets are free from any blend and clearly show broad multi-component structure with at least two components contributing to the absorption. We will refer to the highest velocity component as component-1 and the other as component-2 in subsequent discussions regarding this system (e.g. in section 5.2). There is only a mild contamination from Ly $\gamma$  of  $z_{\text{abs}} = 0.3488$  absorber in the blue wing of the Mg X  $\lambda 609$  line as shown by shaded region. The red wing of the Mg X  $\lambda 624$ , on the other hand, is blended with O IV  $\lambda 608$  transitions from another associated absorber (i.e.  $z_{\text{abs}} = 1.21534$ ) along this sight line. We use the uncontaminated core pixels (i.e., between  $-8350 < v (\text{km s}^{-1}) < -8150$ ) of Mg X doublets and estimate the covering fraction  $f_c = 0.8 \pm 0.1$  (see Fig. 10). Na IX  $\lambda 681$  line is completely free from any contamination and shows remark-

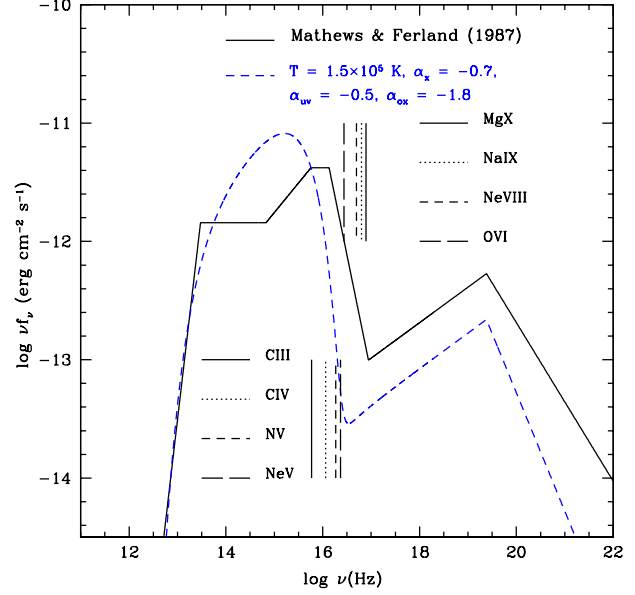




**Figure 10.** Profiles of Mg X doublet for the system at  $z_{\text{abs}} = 1.15456$  towards PG 1338+416 are shown in the two bottom panels. Corresponding apparent column density distributions [in units of  $10^{13} \text{ cm}^{-2} (\text{km s}^{-1})^{-1}$ ] are shown in the second panel from the top. The covering fraction distribution is shown in the topmost panel. The dashed line indicates the median value of covering fraction  $f_c = 0.8 \pm 0.1$ , as measured in the core pixels. The shaded regions show the velocity range affected by unrelated absorption.

able similarity with Mg X profiles. This possibly means Mg X and Na IX are originating from the same phase of the absorbing gas. The red wing of Na IX  $\lambda 694$  line, however, is blended by Ly-9 transition from a previously known DLA at  $z_{\text{abs}} = 0.6214$  (Rao et al. 2006). Therefore we use covering fraction for Na IX similar to that of Mg X. We note that such an assumption gives remarkably good fit to Na IX doublets.

Both transitions of Ne VIII doublet show very strong, albeit blended, absorption with flat bottom profiles consistent with  $f_c = 0.8$ . The strong uncontaminated O V and Ne VI lines also show flat bottom profiles. The covering fraction in these two cases, as calculated from the flat bottom, are very similar and lower (i.e.  $f_c = 0.67$ ) than that of very highly ionized species (i.e. Ne VIII, Mg X). Clearly, like the previous case (i.e.  $z_{\text{abs}} = 1.02854$  towards PG 1206+459), here also we find two sets of covering fraction for the detected species suggesting ionization potential dependent phase separation of the absorbing gas. Ne V line seen in this absorber is unsaturated and shows two possible velocity components. However, due to severe blending in both the wings of Ne V absorption, we only estimate the upper limit on  $N(\text{Ne V})$  assuming  $f_c$  and  $b$ -parameters similar to those of O V line. In section 5, we will show that, under photoionization equilibrium O V and Ne V trace each other for the whole range of ionization parameters. Therefore, using the O V covering fraction for Ne V is legitimate. We also estimate upper limits on the weak absorption seen in the expected position of Al XI  $\lambda 550$  transition assuming  $f_c$  and  $b$ -parameters similar to those of Mg X, as they have ionization potentials of similar order. However, as both the wings of Al XI  $\lambda 550$  line is blended the measured column density is merely an upper limit. The other member of Al XI doublet with  $\lambda_{\text{rest}} = 568 \text{ \AA}$ , is severely affected by the



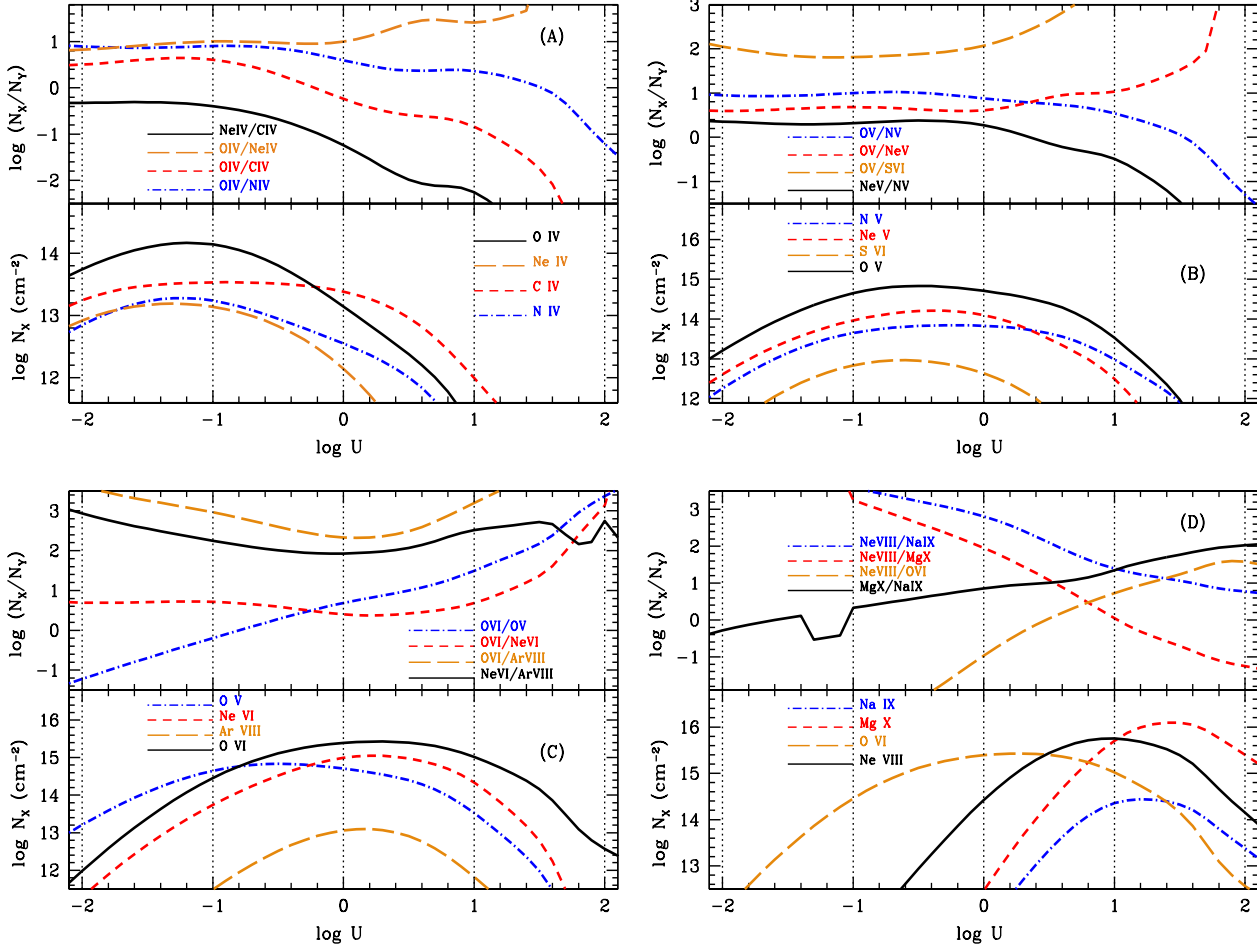
**Figure 11.** Typical shapes of spectral energy distributions of an AGN with arbitrary normalization. The solid line gives the spectrum by Mathews & Ferland (1987) whereas the dotted curve is generated assuming a blackbody with temperature  $T_{\text{BB}} \sim 1.5 \times 10^5 \text{ K}$  and power laws with typical slopes,  $\alpha_{\text{uv}} = -0.5$ ,  $\alpha_x = -0.7$  and  $\alpha_{\text{ox}} = -1.8$  (see text). The vertical lines with different line styles mark the frequency corresponding to the ionization potential of the species mentioned in the plot.

Galactic Ly $\alpha$  absorption and complex blend. In addition, we do not detect any clear signature of Ly $\alpha$  absorption, in the FOS/G270H spectrum. Some absorption is seen in the expected positions of O VI doublets in the FOS/G190H spectrum. However, the contamination of O VI lines from  $z_{\text{abs}} = 1.16420$  absorber and the poor data quality prevent us from any reliable column density estimations. The partial coverage corrected Voigt profile fit parameters are given in Table 7. In the case of non-detections (i.e. H I, O IV and Ar VIII), we present  $3\sigma$  upper limits on column densities as estimated from the error in the continuum.

## 5 IONIZATION MODELS

In this section, we try to determine the ionization structure and the physical conditions in the outflowing gas with the help of photoionization equilibrium models using CLOUDY v(07.02) (first described in Ferland et al. 1998). First, we describe results of a general photoionization model to understand the variation of column densities of different high and low ions and their ratios over a wide range in ionization parameter. We then describe more detailed models (both PI and CI) only for those individual absorbers showing absorption lines from several ions with adequate column density measurements.

Our photoionization models assume the absorbing gas to be an optically thin (i.e. stopping H I column density of  $10^{14} \text{ cm}^{-2}$  as measured in most cases) plane parallel slab with solar metallicity and relative solar abundances, illuminated by the AGN spectrum. To draw some general conclusions we use the mean spectrum of Mathews & Ferland (1987) (hereafter MF87, see solid curve in Fig. 11). However, it is well known that the results of photoionization modeling is very sensitive to the shape of the ionizing radi-



**Figure 12.** Results of photoionization model calculation in optically thin condition with  $N(\text{H I}) = 10^{14} \text{ cm}^{-2}$ , incident ionizing continuum given by Mathews & Ferland (1987), and with solar metallicity ( $Z = Z_{\odot}$ ). In each panel column densities of various species (bottom) and their ratios (top) are plotted as a function of ionization parameter. A species will be detectable for the ionization parameter range in which it has column density  $N \gtrsim 10^{13} \text{ cm}^{-2}$ . In the detectable range if two species show constant ratio (i.e. insensitive to ionization parameter), they are likely to originate from the same phase of the absorbing gas. Such a pair of ions is good to estimate relative abundance of the elements. Ionization parameter should be estimated from the pair of ions whose ratio is sensitive to the  $\log U$ . Note that, according to the ionization potentials, different species are grouped and plotted in different panels for convenience. The notch seen in the  $N(\text{Mg X})/N(\text{Na IX})$  ratio in panel-(D) is an artifact created by CLOUDY in the low column density limit of  $N(\text{Mg X})$ .

tion. In order to minimize the uncertainties, while modelling individual absorbers, we use the QSO SED of the form:

$$f_{\nu} = \nu^{\alpha_{\text{uv}}} \exp(-h\nu/kT_{\text{BB}}) \exp(-kT_{\text{IR}}/h\nu) + B\nu^{\alpha_{\text{x}}}, \quad (3)$$

while discussing individual systems. Here,  $T_{\text{BB}}$ ,  $\alpha_{\text{uv}}$  and  $\alpha_{\text{x}}$  are disk black body temperature, UV spectral index and X-ray spectral index respectively. The normalization constant  $B$  is fixed using the optical-to-X-ray powerlaw slope  $\alpha_{\text{ox}}$  and we use  $kT_{\text{IR}} = 0.01$  Rydberg. We use the SED defined by the Eq. 3 with appropriate values for the parameters (based on available observations) when we discuss the photoionization models of individual absorbers.

The model predictions for MF87 incident continuum are plotted in Fig. 12. In the bottom of each panel, we plot the column densities of different species having similar ionization potential, as a function of ionization parameter. For the sensitivity of our COS spectra, we find that the column density of individual species has to be  $\geq 10^{13} \text{ cm}^{-2}$  to produce detectable absorption lines which are as broad as  $\sim 100 \text{ km s}^{-1}$ .

In panel (A) of Fig. 12, we plot the model predictions for the species N IV (I.P = 47.5 eV), C IV (I.P = 47.9 eV), O IV (I.P = 54.9

eV) and Ne IV (I.P = 63.5 eV). Among all these species, O IV seems to be the dominant in the range  $-2.0 \leq \log U \leq 0.0$  and apart from C IV all of them showing peak round  $\log U \sim -1.0$  (see bottom panel). C IV, however, shows relatively flat distribution over the above mentioned ionization parameter range. For  $\log U > 0.0$ , column densities of almost all these species become  $< 10^{13} \text{ cm}^{-2}$  and hence, they will not be detectable. From the top panel it is clear that the ionization parameter range where all the species are detectable (i.e.,  $-2.0 \leq \log U \leq 0.0$ ),  $N(\text{O IV})/N(\text{N IV})$  and  $N(\text{O IV})/N(\text{Ne IV})$  ratios show remarkable constancy. The ratios where  $N(\text{C IV})$  is involved [i.e.  $N(\text{Ne IV})/N(\text{C IV})$  and  $N(\text{O IV})/N(\text{C IV})$ ], on the other hand, show similar constancy for  $-2.0 \leq \log U \leq -1.0$  and fall by a factor of  $\geq 0.84$  dex in the range  $-1.0 \leq \log U \leq 0.0$ .

In panel (B) we plot the model predictions for the species S VI (I.P = 72.7 eV), O V (I.P = 77.4 eV), N V (I.P = 77.5 eV) and Ne V (I.P = 97.1 eV). From the bottom panel, it is apparent that O V is the dominant species for the whole range in ionization parameters. In addition, all of them show roughly similar  $N$  distribution with a



**Table 7.** Partial coverage corrected Voigt profile fit parameters for  $z_{\text{abs}} = 1.15456$  towards PG 1338+416.

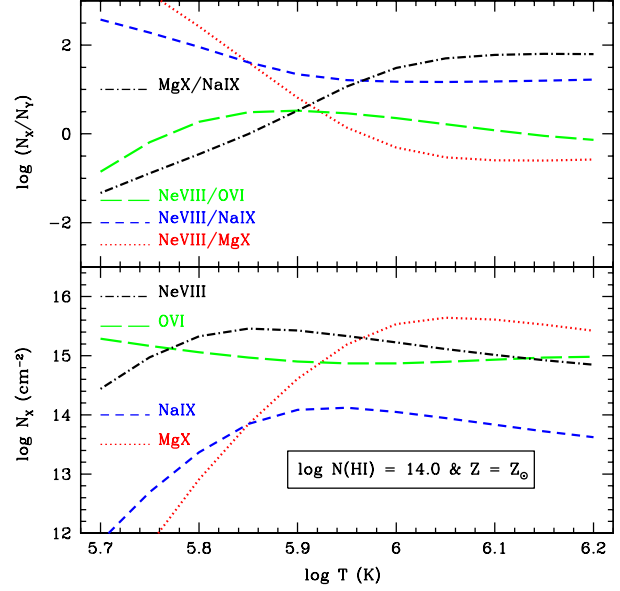
| $v_{\text{ej}}(\text{km s}^{-1})$ | Ion     | $b(\text{km s}^{-1})$ | $\log N(\text{cm}^{-2})$ | $f_c^a$   |
|-----------------------------------|---------|-----------------------|--------------------------|-----------|
| (1)                               | (2)     | (3)                   | (4)                      | (5)       |
| -8195                             | Na IX   | $165 \pm 12$          | $15.05 \pm 0.03$         | 0.80 (aa) |
|                                   | Mg X    | $165 \pm 7$           | $15.62 \pm 0.02$         | 0.80 (db) |
|                                   | Al XI   | 165                   | $\leq 14.77 \pm 0.07$    | 0.80 (aa) |
|                                   | Ne VIII | $89 \pm 35$           | $> 15.94 \pm 0.41$       | 0.80 (fb) |
|                                   | O V     | $91 \pm 6$            | $> 14.97 \pm 0.06$       | 0.67 (fb) |
|                                   | Ne VI   | $87 \pm 5$            | $> 15.57 \pm 0.04$       | 0.67 (fb) |
|                                   | O IV    | 91                    | $\leq 13.69$             | 0.67 (aa) |
|                                   | Ne V    | 91                    | $\leq 15.26$             | 0.67 (aa) |
|                                   | Ne IV   | 91                    | $\leq 13.66$             | 0.67 (aa) |
|                                   | Ar VIII | 91                    | $\leq 13.94$             | 0.67 (aa) |
|                                   | H I     | 165                   | $\leq 13.64$             | 0.67 (aa) |
|                                   | H I     | 165                   | $\leq 13.56$             | 0.80 (aa) |
| -8055                             | Na IX   | $90 \pm 8$            | $14.82 \pm 0.04$         | 0.80 (aa) |
|                                   | Mg X    | $86 \pm 5$            | $15.33 \pm 0.03$         | 0.80 (db) |
|                                   | Al XI   | 86                    | $\leq 14.66 \pm 0.06$    | 0.80 (aa) |
|                                   | Ne VIII | $62 \pm 6$            | $> 15.45 \pm 0.12$       | 0.80 (fb) |
|                                   | O V     | $65 \pm 5$            | $> 14.85 \pm 0.08$       | 0.67 (fb) |
|                                   | Ne VI   | $66 \pm 5$            | $> 15.60 \pm 0.07$       | 0.67 (fb) |
|                                   | O IV    | 65                    | $\leq 13.90$             | 0.67 (aa) |
|                                   | Ne V    | 65                    | $\leq 14.87$             | 0.67 (aa) |
|                                   | Ne IV   | 65                    | $\leq 13.10$             | 0.67 (aa) |
|                                   | Ar VIII | 65                    | $\leq 13.30$             | 0.67 (aa) |
|                                   | H I     | 91                    | $\leq 13.50$             | 0.67 (aa) |
|                                   | H I     | 91                    | $\leq 13.42$             | 0.80 (aa) |

Table Note – <sup>a</sup> Same as Table 4

peak around  $\log U \sim -0.5$ . We also find that most of these species are detectable in the range  $-1.5 \leq \log U \leq 0.5$ . From the top panel, it is interesting to note that, apart from  $N(\text{O V})/N(\text{S VI})$  ratio, all other ratios are exceptionally constant over the ionization parameter range where these species are detectable (i.e.  $-1.5 \leq \log U \leq 0.5$ ).

In panel (C) we plot the model predictions for the species O V (I.P = 77.4 eV), O VI (I.P = 113.9 eV), Ar VIII (I.P = 124.3 eV) and Ne VI (I.P = 126.2 eV). From the bottom panel, it is evident that, apart from Ar VIII all other species are detectable roughly in the range  $-1.0 \leq \log U \leq 1.0$ . In addition, O VI is found to be the dominant species in this ionization parameter range. Ar VIII, on the other hand, is detectable in a very narrow range in ionization parameter around  $\log U \sim 0.0$ , where all these species show peak column densities. From the top panel, it is interesting to note that the  $N(\text{O VI})/N(\text{O V})$  ratio keeps on increasing with the increase of ionization parameter whereas  $N(\text{O VI})/N(\text{Ne VI})$  ratio remains constant for the entire range in  $\log U$  (i.e.  $-2.0 \leq \log U \leq 1.0$ ). The  $N(\text{Ne VI})/N(\text{Ar VIII})$  ratio also remains constant in the range  $-1.0 \leq \log U \leq 1.0$ .  $N(\text{O VI})/N(\text{Ar VIII})$  ratio, on the contrary, varies by a factor of  $\sim 6$  in the same ionization parameter range.

In panel (D), we plot the model predictions for the high ionization species e.g., O VI (I.P = 113.9 eV), Ne VIII (I.P = 207.3 eV), Na IX (I.P = 264.2 eV) and Mg X (I.P = 328.2 eV). From the bottom panel, we note that Na IX and Mg X are detectable only for  $\log U \gtrsim 0.5$  and their column densities show peak at  $\log U \sim 1.4$ . Ne VIII, on the other hand, shows peak at  $\log U \sim 1.0$  and  $N(\text{Ne VIII}) > 10^{13} \text{ cm}^{-2}$  for  $\log U \gtrsim -0.5$ . O VI, in contrast, shows relative flat distribution and is detectable for the entire range in ionization parameter (e.g.  $-1.5 \leq \log U \leq 1.8$ ). It is interesting to note that the ratios plotted in the top panel show smooth variation over the whole range in ionization parameter. For example,  $N(\text{Mg X})/N(\text{Na IX})$  ratio varies by a factor  $\sim 3$  in the range  $0.0 \leq$

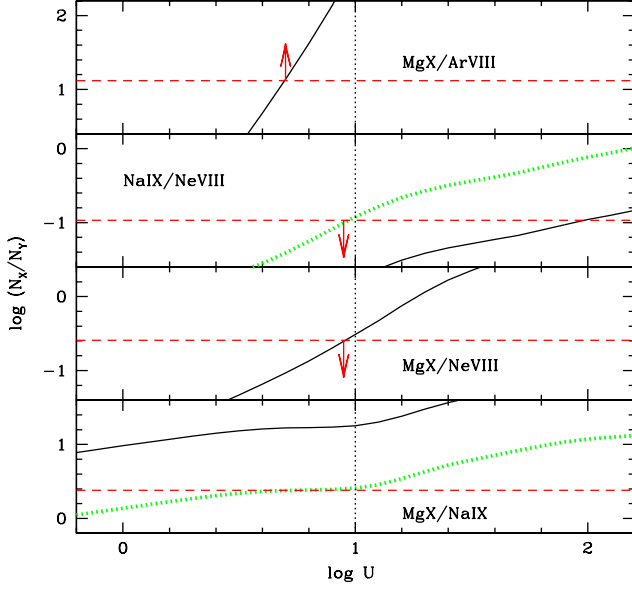
**Figure 13.** *Bottom* : Column densities of various high ionization species as a function of gas temperature under collisional ionization equilibrium (Sutherland & Dopita 1993). Column densities are calculated for  $N(\text{H I}) = 10^{14} \text{ cm}^{-2}$ , assuming solar metallicity. *Top* : Column density ratios are plotted as a function of gas temperature.

$\log U \leq 1.0$  and by a factor  $\sim 5$  in the range  $1.0 \leq \log U \leq 2.0$ . Note that notch seen in  $N(\text{Mg X})/N(\text{Na IX})$  ratio around  $\log U = -1.2$  is not real but a numerical artifact where  $N(\text{Mg X})$  become negligibly small.

The above analysis clearly provides the rough range in the ionization parameter where species with similar ionization potentials are most likely to originate from the same phase of the absorber. In this  $U$  range the ratios of such ionic column densities are also useful in constraining the relative abundances of the heavy elements. On a different note, we wish to point out here that all these species originating from same phase (or density) will have similar projected area and hence they will show very similar covering fractions. The ratios of very highly ionized species (i.e. O VI, Ne VIII, Na IX and Mg X that are the main focus of this work) show smooth variation over ionization parameter. These ratios are sensitive probes of the ionization parameter provided these species originate from the same phase of the absorbing gas. The nature of absorption profiles (e.g. velocity alignment, line spread, component structure etc.) can be used to decide whether these species originate from the same phase of the absorbing gas.

Muzahid et al. (2012b) have shown that the near constancy of  $N(\text{O VI})/N(\text{Ne VIII})$  between different components in the associated absorber towards HE 0238-1904 can be explained if collisional excitation plays an important role. Therefore, we now consider the collisional ionization equilibrium (CIE) model (Sutherland & Dopita 1993). The model predicted column densities of high ionization species discussed in the panel-(D) of Fig. 12 are plotted as a function of gas temperature, in the lower panel of Fig. 13. The column densities are calculated for  $N(\text{H I}) = 10^{14} \text{ cm}^{-2}$  and  $Z = Z_{\odot}$ , typically seen in most of the cases in our sample. It is clear from the figure that for  $\log T > 6.0$ , all these high ionization species become fairly insensitive to the gas temperature.





**Figure 14.** Photoionization model for the system  $z_{\text{abs}} = 1.02854$  towards PG 1206+459. CLOUDY predicted column density ratios of various high ionization species as a function of ionization parameter are plotted in different panels. The horizontal dashed line in the bottom panel indicates the measured value of  $N(\text{Mg X})/N(\text{Na IX})$  in component-1. In all other cases the horizontal dashed line marks the upper/lower limit on the ratio as shown by an arrow. The dotted (green) curves are the model prediction in case of Na is overabundant by a factor of 7 relative to Mg and/or Ne. The dotted vertical line represents a possible solution for the ionization parameter.

This fact is also manifested in the column density ratios, plotted in the top panel.

In what follows we provide detailed models for some individual systems (specially the ones that show Na IX) in the framework of photoionization and CIE models.

### 5.1 Models for the system $z_{\text{abs}} = 1.02854$ towards PG 1206+459

Here we discuss the physical conditions in the  $z_{\text{abs}} = 1.02854$  system towards PG 1206+459. The ionizing background is characterized by the Eq. 3 with  $T_{\text{BB}} \sim 1.5 \times 10^5$  K,  $\alpha_{\text{ox}} = -1.7$ ,  $\alpha_x = -0.7$  and  $\alpha_{uv} = -0.5$ . The value of  $\alpha_{\text{ox}}$  has been calculated assuming power law shape of X-ray spectrum with photon index,  $\Gamma_{0.3-12\text{keV}} = -1.74 \pm 0.09$  (or  $\alpha_x \sim -0.7$ ) and normalization at 1keV is  $A_{\text{PL}} = (2.4 \pm 0.2) \times 10^{-4}$  photons  $\text{cm}^{-2}\text{keV}^{-1}\text{s}^{-1}$ , as estimated for this source by Piconcelli et al. (2005). Using the black hole mass,  $M_{\text{BH}} = 1.0 \times 10^9 M_{\odot}$ , and  $L_{\text{Bol}}/L_{\text{Edd}} = 0.84$  from Chand et al. (2010), the inner disk temperature ( $T_{\text{BB}}$ ) is found to be very similar to the value used here.

From Fig. 7 (and Table 4) we notice that the covering fractions for Na IX, Ne VIII, O V, Mg X and Ar VIII are similar. It is clear that Ne VIII and O V column density estimation are lower limits as they are affected by saturation effects. The photoionization model predictions for the above mentioned SED is given in Fig. 14. The horizontal dashed line in each panel represents the observed values for the component 1 (i.e.,  $v_{\text{ej}} \sim -19,250$  km  $\text{s}^{-1}$  component in Table 4). The upper limit on the observed  $N(\text{Mg X})/N(\text{Ne VIII})$  ratio, suggests  $\log U \leq 1.0$ . The lower limit

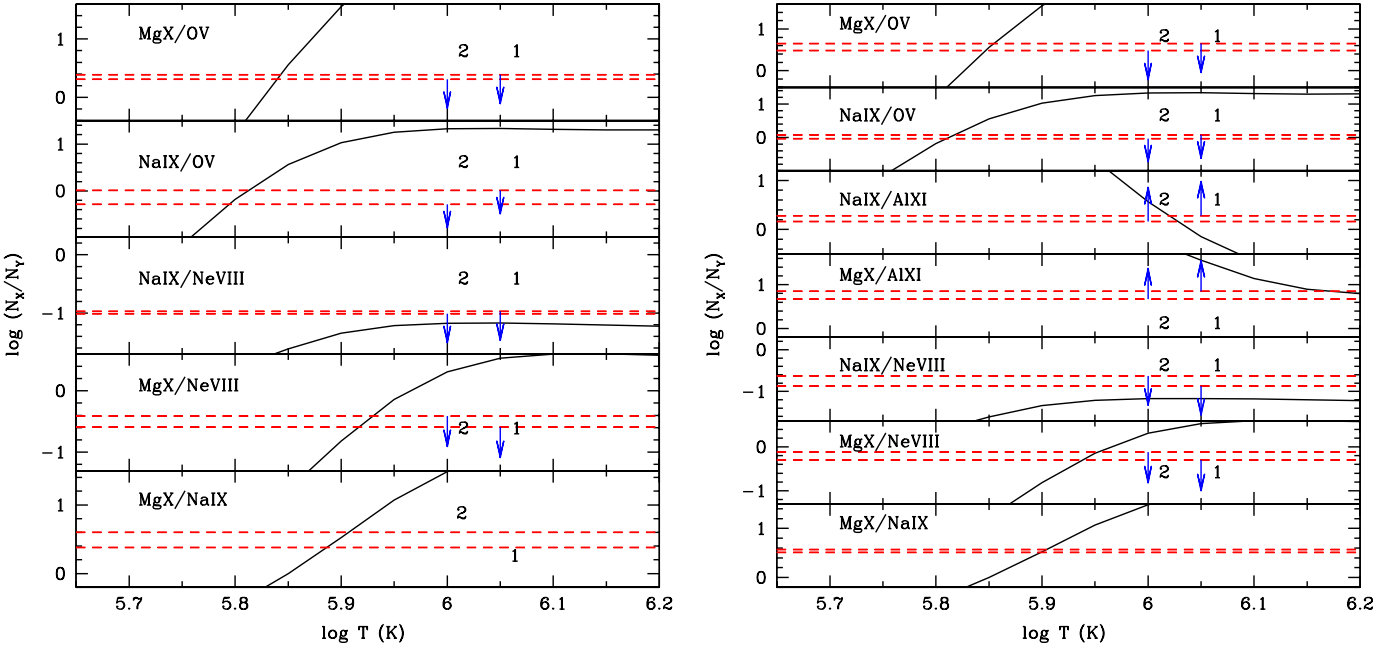
on the observed  $N(\text{Mg X})/N(\text{Ar VIII})$  ratio, on the other hand suggests  $\log U \geq 0.7$ . We notice that in this ionization parameter range (i.e.  $0.7 \leq \log U \leq 1.0$ ) the model over-predicts the observed  $N(\text{Mg X})/N(\text{Na IX})$  ratio. The observed column density ratios involving Na IX can be reproduced by the models if we assume Na is enhanced by a factor of 0.85 dex with respect to Mg and/or Ne [see the dotted (green) curves in Fig. 14]. We estimate the upper limit for  $\log N(\text{H I}) (\text{cm}^{-2}) = 13.78$  using  $f_c = 0.59$  (see Table 4). For this model predicts  $\log N(\text{Mg X}) (\text{cm}^{-2}) = 15.32$ , which is very close to the observed value implying the metallicity of the gas phase producing Ne VIII and Mg X is higher than solar. Among the other species detected in this component only O IV column density and covering fraction are well measured. We find  $N(\text{O IV})$  predicted by our model for  $\log U \sim 1$  is a factor 25 times smaller than what is observed. This confirms that O IV is originating from a distinctly different phase as suggested by the low covering fraction as well. The observed column density of O IV for solar metallicity and  $\log N(\text{H I}) (\text{cm}^{-2}) = 14.42$  (for the similar covering fraction measured for O IV) we find  $\log U \sim 0$ . This ionization parameter also produces the correct value of observed  $N(\text{N IV})$ . If both these phases are at the same distance from the QSO then we can conclude that there is a factor ten change in the density along the transverse direction for the absorbing gas.

In the case of component-2 (i.e.,  $v_{\text{ej}} \sim -19,150$  km  $\text{s}^{-1}$  component in Table 4), the upper limit on observed  $N(\text{Mg X})/N(\text{Ne VIII})$  ratio, suggests  $\log U \leq 1.0$ . The lower limit on observed  $N(\text{Mg X})/N(\text{Ar VIII})$  ratio, on the other hand suggests  $\log U \geq 0.8$ . As in the case of component-1 for this ionization parameter range the photoionization model over predicts the observed  $N(\text{Mg X})/N(\text{Na IX})$ . We find that the observed column density ratios involving Na IX can be reproduced by the model if we assume Na is enhanced by a factor of 0.60 dex with respect to Mg and/or Ne. Like in the previous case the model that reproduces the high ions under-predicts the O IV column density. We also find O IV is originating from a phase that is up to a factor 10 lower density if both phases are at same distance from the QSO.

In both the components N V absorption is detected. The measured column densities are consistent with an ionization parameter intermediate between the gas traced by N IV/O IV and Mg X. All this suggests that the outflow having smooth density gradients in the transverse direction.

For  $\log U=1$ , the inferred total column density of system is  $N(\text{H}) = 4.7 \times 10^{20} \text{ cm}^{-2}$  (when  $\log N(\text{H I}) (\text{cm}^{-2}) = 14.0$ ), whereas, O VII and O VIII column densities are  $N(\text{O VII}) = 1.0 \times 10^{17} \text{ cm}^{-2}$  and  $N(\text{O VIII}) = 9.5 \times 10^{16} \text{ cm}^{-2}$ , suggesting continuum optical depths of O VII and O VIII are much less than 0.1. Therefore, this system may not be a potential X-ray WA candidate.

In the left hand panel of Fig. 15, the column density ratios of various high ionization species predicted by the CIE models, are plotted as a function of gas temperature. The horizontal dashed lines followed by arrows, in each sub-panel except for the bottom one, indicate the upper limit on the column density ratios measured in component-1 and component-2. The measured values of  $N(\text{Mg X})/N(\text{Na IX})$  ratio, shown in the bottom panel, are found to be very similar for both the components which corresponds to a temperature of  $\log T \sim 5.9$ . Note that the upper limits on  $N(\text{Mg X})/N(\text{Ne VIII})$  ratios observed in both the components suggests  $\log T \lesssim 5.9$ . The observed value of  $N(\text{O V})$ , on the other hand, suggests a temperature  $T \sim 10^{5.8}$  K. On the other hand we notice that low ionization species like O IV and N IV require  $T \sim 10^{5.2}$  K. In order for the two phases to be in pressure equilib-



**Figure 15.** *Left:* CIE model for the system at  $z_{\text{abs}} = 1.02854$  towards PG 1206+459. *Right:* CIE model for the system at  $z_{\text{abs}} = 1.15456$  towards PG 1338+416. In each panel model predicted column density ratios of various high ionization species are plotted as a function of gas temperature. In the bottommost panels the horizontal dotted line represents the measured  $N(\text{Mg X})/N(\text{Na IX})$  ratios in component-1 and component-2. In all other panels horizontal dotted lines followed by an arrow mark the observed upper/lower limits on the plotted ratios.

rium the density of the low ionization phase needs to be a factor 4 higher. We next run CLOUDY model keeping the gas temperature to be constant at  $T \sim 10^{5.8}$  K and found that the ionization parameter of the gas  $\log U \leq -2$  so that the ratio of Mg X and Ne VIII are not affected by the QSO radiation. Given the luminosity of the QSO this corresponds to a radial separation of  $\gtrsim 2600/\sqrt{(n_{\text{H}}/10^5)}$  pc between the absorbing gas and the QSO, so that the ionization state can be dominated by collisions.

## 5.2 Models for the system $z_{\text{abs}} = 1.15456$ towards PG 1338+416

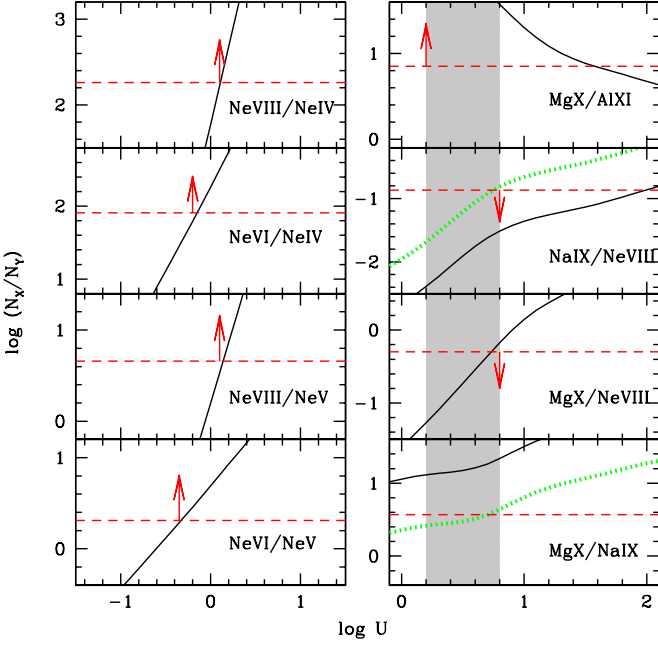
Here we discuss the photoionization model for the system  $z_{\text{abs}} = 1.15456$  towards PG 1338+416. For SED we use  $T_{\text{BB}} \sim 1.0 \times 10^5$  K,  $\alpha_{\text{x}} = -1.5$ ,  $\alpha_{\text{uv}} = -0.5$  and  $\alpha_{\text{ox}} = -1.8$  (from Anderson et al. 2007). From the Mg II emission line width Chand et al. (2010) have estimated the black hole mass for this source to be  $\log M_{\text{BH}}/M_{\odot} \sim 8.96$  and 9.47 using the method by McLure & Dunlop (2004) and Dietrich et al. (2009) respectively. They also find  $L_{\text{bol}}/L_{\text{Edd}} = 0.34$  for this source. Using these we calculate the inner disk temperature for this QSO to be  $T_{\text{BB}} \sim 1.2 \times 10^5$  K and  $9.1 \times 10^4$  K for  $\log M_{\text{BH}}/M_{\odot} \sim 8.96$  and 9.47 respectively. This is close to what we use to generate the SED.

In Fig. 16 we show the results of our photoionization model. In the left hand panel of the figure we have shown the column density ratios of different ionization states of neon. All these ratios gives lower limits on ionization parameter. The best constraint comes from  $N(\text{Ne VIII})/N(\text{Ne V})$  ratio, which suggests  $\log U \geq 0.2$ . All other ratios are consistent with this lower limit. In the right hand panel we have plotted ionic ratios of different species of different elements which can provide useful constraints on the ionization parameter (see section 5). The observed

upper limit on  $N(\text{Mg X})/N(\text{Ne VIII})$  ratio suggests  $\log U \leq 0.8$ . Hence the physically allowed range in ionization parameter becomes  $0.2 \leq \log U \leq 0.8$ , as marked by the shaded region. We note that the observed limits on  $N(\text{Mg X})/N(\text{Al XI})$  and/or  $N(\text{Mg X})/N(\text{O V})$  are also consistent with this range. However, it is apparent from the right-bottom panel, that our model cannot reproduce the observed  $N(\text{Mg X})/N(\text{Na IX})$  ratio for the whole range in ionization parameter, where the individual species (i.e. Na IX and Mg X) are detectable. Similarly,  $N(\text{Na IX})/N(\text{Ne VIII})$  ratio also suggests a very high  $\log U$ , which is not in the allowed range of ionization parameter (i.e. shaded region). Like the previous case (see section 5.1), such a discrepancy can be easily avoided if Na is overabundant by factor of  $\sim 5$ –6, as can be seen from the dotted (green) curves in the figure.

Assuming  $\log U = 0.5$  and using the estimated upper limit on  $N(\text{H I})$  in the component-1 [i.e.  $\log N(\text{H I}) (\text{cm}^{-2}) \leq 13.64$ ; see Table 7], we estimate the metallicity of the gas to be  $\gtrsim 10 Z_{\odot}$ . The total column density of the system at  $\log U \sim 0.5$  is  $\log N(\text{H}) (\text{cm}^{-2}) = 20.09$ . Predicted column densities of O VII and O VIII are  $\log N (\text{cm}^{-2}) = 17.47$  and 17.02 respectively. Continuum optical depth of oxygen corresponding to these values is again much less than 0.1, suggesting that the system may not be a potential X-ray WA candidate.

From the right hand panel of Fig. 15, we can conclude that the observed ratios and limits of high ions can be explained if the gas temperature is  $T \sim 10^{5.9}$  K without the enhancement of Na as required by the photoionization models. However, in order for the QSO radiation field to not affect the ionization state of the absorbing gas the ionization parameter has to be  $\log U \leq -1.0$ . For the inferred luminosity this corresponds to a separation of  $\gtrsim 400/\sqrt{(n_{\text{H}}/10^5)}$  pc of the absorbing cloud from the QSO.



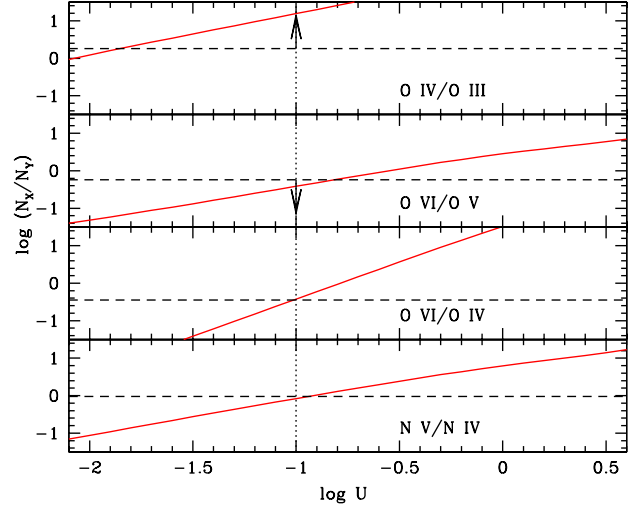
**Figure 16.** Photoionization model for the system  $z_{\text{abs}} = 1.15456$  towards PG 1338+416. CLOUDY predicted column density ratios of different ions are plotted as a function of ionization parameter in different panels. The horizontal (red) dashed line followed by an arrow in each panel represents the observed upper/lower limit on the plotted ratio as measured in component-1. *Left* : Ratios of different ionization states of neon are plotted. *Right* : Same as *Left* but for different ionization states of different elements. The dotted (green) curves are the model prediction in case of Na is overabundant by a factor of 5 relative to Mg and/or Ne. The shaded region represents the allowed range in ionization parameter as suggested by various ionic ratios.

### 5.3 Model for the system $z_{\text{abs}} = 1.21534$ towards PG 1338+416

In this section we discuss the photoionization model for  $z_{\text{abs}} = 1.21534$  absorber towards PG 1338+416. This system has  $z_{\text{abs}}$  very similar to  $z_{\text{em}} = 2.2145 \pm 0.0019$ . This is the only associated Ne VIII system along the line of sight without detectable Na IX absorption. Unlike this system the other two have large outflow velocities and show signatures of partial coverage. The column density of Ne VIII is also high in the other two systems.

In section 4.8, we have seen that the low ionization species, detected in COS, originating from this system show 2 possible components. However, because of the poor spectral resolution, species detected in *HST*/FOS spectra can be well fitted by a single Voigt profile component. Because of this disparity in the data quality, we use the total column densities (i.e. summed up component column densities), for the photoionization model. We run CLOUDY with same set of parameters as described in section 5.2. The results of our photoionization model are shown in Fig. 17.

The column density ratios of different ionization states of same element are very important diagnostics of ionization parameter. Therefore, we make use of simultaneous presence of O III, O IV, O V and O VI lines of oxygen and N IV and N V lines of nitrogen to estimate the ionization parameter of the gas. Since we treat  $N(\text{O III})$  and  $N(\text{O V})$  as upper and lower limits (see discussions in section 4.8), the ionization parameter is primarily decided by  $N(\text{O VI})/N(\text{O IV})$  and  $N(\text{N V})/N(\text{N IV})$  ratios. It is clear from

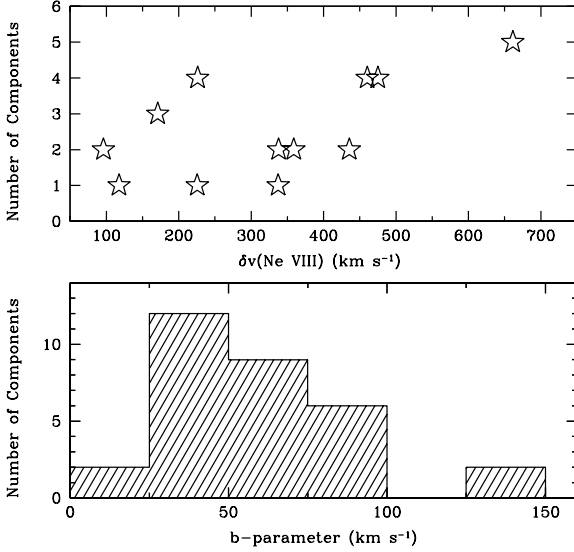


**Figure 17.** Photoionization model for the system  $z_{\text{abs}} = 1.21534$  towards PG 1338+416. CLOUDY predicted column density ratios of different ions are plotted as a function of ionization parameter in different panels. The horizontal dashed line in the bottom two panels mark the measured ionic ratios. The dashed lines with arrows in the top two panels show measured limits on the ionic ratios. The vertical dotted line at  $\log U = -1$  marks a possible solution for the ionization parameter.

Fig. 17 that, both the ratios are remarkably consistent with  $\log U \sim -1.0$ . We also note that, the upper limit on  $N(\text{O VI})/N(\text{O V})$  and lower limits on  $N(\text{O IV})/N(\text{O III})$  ratios are also suggestive of such an ionization parameter. Using the ionization fractions at  $\log U \sim -1.0$ , we find that the metallicity of the gas to be near solar, e.g.  $\log Z/Z_{\odot} = 0.40^{+0.90}_{-0.25}$ .

In the section 5, we have seen that the species N IV and O IV traces each other for a wide range in ionization parameter. Therefore,  $N(\text{N IV})/N(\text{O IV})$  ratio is a sensitive probe of the relative abundances. From the observed  $N(\text{N IV})/N(\text{O IV})$  ratio we find that nitrogen is overabundant compared to oxygen by a factor of 0.93 dex (i.e.,  $[\text{N}/\text{O}] = 0.07$ ). Furthermore, nitrogen is found to be overabundant compared to carbon by a factor of 0.89 dex (i.e.  $[\text{N}/\text{C}] = 0.29$ ), from the measured  $N(\text{N IV})/N(\text{C III})$  ratio. Since O III line is blended, we use  $N(\text{C III})/N(\text{O IV})$  ratio to estimate  $[\text{C}/\text{O}]$  and found that the carbon and oxygen roughly follow solar abundance pattern. For example, estimated  $[\text{C}/\text{O}] = -0.22$ , whereas, in sun  $(\text{C}/\text{O}) = -0.26$  (Asplund et al. 2009). Such an enhanced nitrogen abundance is seen in high redshift ( $z \geq 2.0$ ) QSOs (Hamann & Ferland 1992; Korista et al. 1996; Petitjean & Srianand 1999). These authors suggested a rapid star formation scenario which produces a super solar metallicity in order to boost the nitrogen abundance through enhanced secondary production in massive stars. We would like to mention that, with the estimated ionization parameter and metallicity, neither Ne VIII nor Mg X would be detectable [e.g., reproduced  $\log N(\text{Ne VIII}) (\text{cm}^{-2}) \ll 14.0$  at  $\log U = -1.0$ ].

The observed  $N(\text{Ne VIII})/N(\text{Mg X})$  ratio require a different phase with fairly high ionization parameter (i.e.,  $\log U \sim 1.3$ ). If we assume most of the O V originate from Ne VIII phase then we get  $\log U \geq 0.8$ . In equality in this case is because some part of O V will originate from O IV phase. If we use  $N(\text{O VI})/N(\text{Ne VIII})$  ratio then we get  $\log U \geq 0.9$ . Thus one can conclude that the Ne VIII absorption is originating from a gas having  $\log U \sim 1$  (as we have



**Figure 18.** *Bottom:* The distribution of Doppler parameter as measured in individual Ne VIII components. *Top:* Number of Ne VIII components against the spread of Ne VIII absorption in each system.

seen in the other cases discussed above). If we assume the Ne VIII phase has same metallicity as the low ionization phase discussed above then we can conclude that H I associated with Ne VIII is  $\leq 10^{12} \text{ cm}^{-2}$ . We can conclude that the low hydrogen column density in this component is the reason for the lack of Na IX absorption in this system.

Like in the previous cases our model suggests that the absorbing gas will not have sufficient optical depth to be a X-ray warm absorber.

## 6 DISCUSSIONS

In this section, we try to draw a broad physical picture of the associated Ne VIII absorbers.

### 6.1 Incidence of associated Ne VIII absorbers

The fraction of AGNs that show associated absorption is important for understanding the global covering fraction and the overall geometry of the absorbing gas (Crenshaw et al. 2003; Ganguly & Brotherton 2008). In low redshift Seyfert galaxies, surveys in the UV (Crenshaw et al. 1999), FUV (Kriss 2002), and X-rays (Reynolds 1997) found  $\sim 50 - 70\%$  incidence of associated absorbers. For quasars, the fraction of occurrence has been found to be somewhat lower. For example Ganguly et al. (2001) found signature of associated C IV absorption in  $\sim 25\%$  of QSOs. On the other hand, (Dai et al. 2008) have found occurrence of BAL in  $\sim 40\%$  cases. However, we note that depending upon the selection criteria (e.g. cutoff velocity, rest frame equivalent width etc.) these numbers could be very different. An exposition on the incidence of different forms of the associated absorbers can be found in Ganguly & Brotherton (2008). We have found 12 associated Ne VIII systems in 8 out of 20 QSOs in our sample while only 2 is expected based on the statistics of intervening systems. Even if we restrict ourself to  $|v_{ej}|$  up to  $5000 \text{ km s}^{-1}$  instead of  $8000$

$\text{km s}^{-1}$ , we have 8 associated systems which is factor 4 higher compared to what is expected from statistics of intervening systems. Such an enhanced occurrence of associated absorbers have also been noticed in the case of high- $z$  (Fox et al. 2008) and low- $z$  (Tripp et al. 2008) O VI absorbers. The incidence of associated Ne VIII absorbers in our sample is  $\sim 40\%$  ( $\sim 35\%$  if we do not include the tentative system towards HB89 0107–025 or restrict to systems with  $|v_{ej}| < 5000 \text{ km s}^{-1}$ ). It is also interesting to note only 5/12 systems along 3/20 sightlines show signature of partial coverage. Therefore the incidence of partially covered associated Ne VIII absorber is 15%. No associated Ne VIII system is detected towards 7 radio bright QSOs in our sample. There are 5 Ne VIII absorption reported in the literature (see Table 8) and only one of them ( $z_{\text{abs}} = 0.965$  towards 3C 288.1) is towards radio bright QSO. Confirming the high detection rate of associated Ne VIII systems and relatively less incidence rate towards radio bright QSOs is very important to understand the possible influences of radio jets.

### 6.2 Line broadening

In the bottom panel of Fig. 18 we show the distribution of Doppler parameter as measured in individual Ne VIII components. The median value of  $b(\text{Ne VIII})$  is  $\sim 58.7 \text{ km s}^{-1}$ . The upper limit on temperature corresponding to this value is  $10^{6.6} \text{ K}$ . Under CIE, even Ne VIII will not be a dominant species at such high temperatures. The collisional ionization fraction of Ne VIII becomes only  $\sim 3 \times 10^{-3}$  at  $T \sim 10^{6.6} \text{ K}$ . Therefore the width of individual Voigt profile components are most probably dominated by non-thermal motions. We note that  $b(\text{Ne VIII}) \sim 22 \text{ km s}^{-1}$  corresponds to a temperature of  $10^{5.8} \text{ K}$ , at which  $N(\text{Ne VIII})$  peaks under CIE (see bottom panel of Fig. 13). This indeed suggests that, based on the observed  $b$ -values of Ne VIII, we cannot rule out the possibility of gas temperature being  $6-7 \times 10^5 \text{ K}$  at which collisional ionization becomes important. Note that we use minimum number of Voigt profile components needed to have a reduced  $\chi^2 \sim 1$ . The discussions presented above are based on  $b$ -parameters derived this way. While we can not rule out each of our Voigt profile component being made of a blended large number of components, our analysis suggests that the observed line profiles allow for the gas temperature being higher than the typical photoionization equilibrium temperature. In the top panel of Fig. 18 we have plotted the number of components required to fit Ne VIII absorption against the velocity spread of the line. Lack of any significant correlation between these two suggests that the line spread may not dominated by the presence of multiple number of narrow components (as seen in the case of high redshift O VI absorbers, e.g. Muzahid et al. 2012a) but the line spread is related to the large scale velocity field. Further,  $\delta v(\text{Ne VIII})$  lies roughly between  $100 - 800 \text{ km s}^{-1}$  suggesting that these absorbers are intermediate of BAL and NAL. This type of associated absorbers are also known as mini-BAL.

### 6.3 Ejection velocities and correlations

The ejection velocity is defined as the velocity separation between the emission redshift of the QSO and the Ne VIII optical depth weighted redshift of the absorber. The distribution of ejection velocities in our sample are shown in panel (A) of Fig. 19. Clearly most of these associated Ne VIII absorbers are detected within  $-5000 \text{ km s}^{-1}$  from the emission redshift of the QSO. The highest velocity absorber is detected at a ejection velocity of  $\sim -19,000 \text{ km s}^{-1}$ . In panel (B) we have plotted covering fraction corrected

**Table 8.** Summary of associated Ne VIII absorbers from literature (only secure detections are listed here)

| QSO          | $z_{\text{em}}$ | $v_{\text{ej}}(\text{km s}^{-1})$ | $\log N(\text{cm}^{-2})$ |         |      |      |      | Type | QSO Type        | Reference                   |
|--------------|-----------------|-----------------------------------|--------------------------|---------|------|------|------|------|-----------------|-----------------------------|
|              |                 |                                   | O VI                     | Ne VIII | Mg X | H I  | H    |      |                 |                             |
| (1)          | (2)             | (3)                               | (4)                      | (5)     | (6)  | (7)  | (8)  | (9)  | (10)            | (11)                        |
| UM 675       | 2.150           | -1500                             | 15.5                     | 15.4    | .... | 14.8 | 20.0 | NAL  | RQ <sup>b</sup> | Hamann et al. (1995)        |
| SBS 1542+541 | 2.631           | -11360                            | 15.8                     | 16.0    | 15.9 | 14.9 | 22.7 | BAL  | RQ              | Telfer et al. (1998)        |
| J 2233-606   | 2.240           | -3900                             | 15.4                     | 15.1    | .... | 14.0 | 22.0 | NAL  | ...             | Petitjean & Srianand (1999) |
| PG 0946+301  | 1.221           | -10000                            | 16.6                     | 16.7    | 16.6 | 15.3 | .... | BAL  | RQ              | Arav et al. (1999b)         |
| 3C 288.1     | 0.965           | +250                              | 15.8                     | 15.4    | 15.0 | 15.8 | 20.2 | NAL  | RL <sup>a</sup> | Hamann et al. (2000)        |

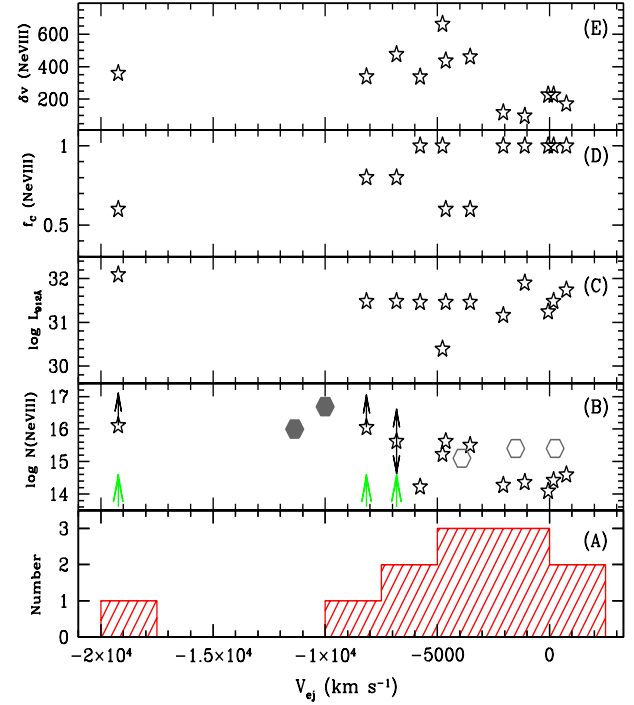
Table Note – <sup>a</sup> Radio Loud; <sup>b</sup> Radio Quiet**Table 9.** List of intervening Ne VIII absorbers that exist in literature

| QSO          | $z_{\text{em}}$ | $z_{\text{abs}}$ | $\log N(\text{cm}^{-2})$ |       | Ref. <sup>a</sup> |
|--------------|-----------------|------------------|--------------------------|-------|-------------------|
|              |                 |                  | Ne VIII                  | O VI  |                   |
| (1)          | (2)             | (3)              | (4)                      | (5)   | (6)               |
| PG 1148+549  | 0.9754          | 0.6838           | 13.95                    | 14.52 | 1                 |
| PG 1148+549  | 0.9754          | 0.7015           | 13.86                    | 14.37 | 1                 |
| PG 1148+549  | 0.9754          | 0.7248           | 13.81                    | 13.86 | 1                 |
| PKS 0405-123 | 0.5726          | 0.4951           | 13.96                    | 14.41 | 2                 |
| 3C 263       | 0.646           | 0.3257           | 13.98                    | 13.98 | 3                 |
| HE 0226-4110 | 0.495           | 0.2070           | 13.89                    | 14.37 | 4                 |

Note– <sup>a</sup>Reference (1) Meiring et al. (2012); (2) Narayanan et al. (2011); (3) Narayanan et al. (2009, 2012) (4) Savage et al. (2005)

total column densities of Ne VIII in our sample (stars) as a function of ejection velocity. The hexagons in this panel are from literature (see Table 8). The overall sample shows a possible correlation between  $N(\text{Ne VIII})$  and  $v_{\text{ej}}$ . If we consider all the limits as detections we find a  $2.1\sigma$  correlation for the systems in our sample. When we consider the measurements from the literature the significance of the correlation increase to  $2.7\sigma$ . However, we note that the top two ejection velocity systems from the literature (filled hexagons) are BAL in nature. The (green) arrows in the bottom, identify the systems with Na IX detection. It is apparent that these are the ones having top three ejection velocities with  $|v_{\text{ej}}| > 5000 \text{ km s}^{-1}$ , in our sample. Interestingly, we note that the only possible Na IX detection was reported before, by Arav et al. (1999b) towards BALQSO PG 0946+301 where the system has an ejection velocity of  $-10,000 \text{ km s}^{-1}$ , which is consistent with the trend seen in our sample.

In panel (C) we have plotted the Lyman continuum luminosity (i.e.  $L_{912\text{\AA}}$  in  $\text{ergs s}^{-1} \text{ Hz}^{-1}$ ) of the sources in our sample as a function of  $v_{\text{ej}}$ . We do not find any obvious correlation between them. However, the highest velocity system, which also show Na IX absorption, originates from the highest UV luminosity source. Here we note that, the sources with higher UV luminosities are found to be the ones with higher outflow velocities in the sample of SDSS BALQSOs (see e.g. Gibson et al. 2009). The estimated Ne VIII covering fractions in different systems in our sample are plotted against the ejection velocity in panel (D). It is to be noted that majority of the systems at smaller ejection velocities show nearly 100% coverage of the background source whereas the systems with higher ejection velocity tend to have lower covering fractions. In panel (E) the line spreads of Ne VIII absorption in each system are plotted as function of  $v_{\text{ej}}$ . A mild  $2\sigma$  level correlation is seen between  $\delta v(\text{Ne VIII})$  and  $v_{\text{ej}}$ , suggesting systems with higher outflow velocity are likely to show wider spread.

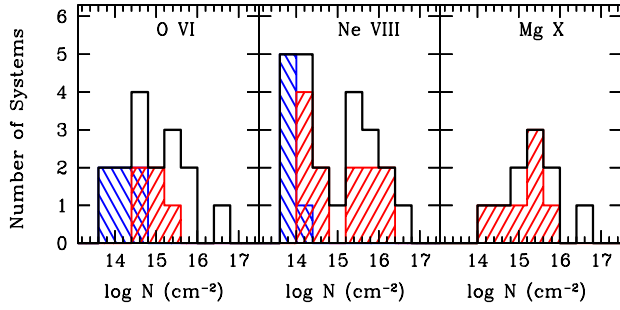


**Figure 19.** (A): The distribution of ejection velocity for the associated Ne VIII absorbers presented in this paper. (B): The Ne VIII column density as a function of ejection velocity. The hexagons are from literature listed in Table 8. The filled hexagons represent BALQSOs. The (green) upward arrows mark the systems where we detect Na IX. (C):  $L_{912\text{\AA}}$  as a function of  $v_{\text{ej}}$ . (D): Ne VIII covering fractions in individual systems against  $v_{\text{ej}}$ . (E): The line spread of Ne VIII absorbers against  $v_{\text{ej}}$ .

#### 6.4 Distribution of column densities

In Fig. 20, we show the column density distributions of the O VI, Ne VIII, and Mg X, as measured in intervening and associated Ne VIII absorbers in our sample and from the existing literature (i.e. using Table 3, 8 and 9). The (blue)  $120^\circ$  and (red)  $60^\circ$  hashed histograms show the distributions corresponding to the intervening Ne VIII systems (i.e. from Table 9) and the associated Ne VIII systems from this paper (i.e. from Table 3) respectively. The histograms clearly show that the column densities of O VI and Ne VIII are systematically higher in case of associated absorbers compared to those of intervening absorbers. For example, the median values of  $\log N(\text{Ne VIII}) (\text{cm}^{-2})$  are  $13.95 \pm 0.10$  and  $15.40 \pm 0.78$  for the intervening and the associated absorbers respectively. The median values of  $\log N(\text{O VI}) (\text{cm}^{-2})$ , on the other hand, are  $14.37 \pm 0.27$  and  $15.40 \pm 0.58$  for intervening and associated absorbers respec-





**Figure 20.** Distribution of total column densities of O VI (left), Ne VIII (middle) and Mg X (right) in all the associated Ne VIII systems (i.e. using Table 3 & 8). The 60° hashed (red) histogram shows the data points from this paper (i.e. using Table 3 only) whereas as 120° hashed (blue) histograms are for measurements in intervening systems as given in Table 9.

tively. However we note that, both at high and low redshifts, O VI absorbers do not show any compelling evidence of having different column density distribution for intervening and associated systems (see e.g. Tripp et al. 2008; Fox et al. 2008). The apparent discrepancy is mainly because of the fact that we consider O VI column densities measured in the Ne VIII absorbers, both in the cases of intervening and associated systems. To our knowledge no Mg X absorption has ever been reported in intervening systems. The median value of  $\log N(\text{Mg X}) (\text{cm}^{-2})$  in associated systems turns out to be  $15.47 \pm 0.66$ . The median values of O VI, Ne VIII, and Mg X in our sample are very similar. But we caution here that we have assumed all the upper/lower limits as measurements.

It is evident from the middle panel of Fig. 20 that all the associated absorbers show  $N(\text{Ne VIII}) > 10^{14} \text{cm}^{-2}$ . This could primarily be due to the fact that we are not sensitive enough to detect a broad line with  $N(\text{Ne VIII}) < 10^{14} \text{cm}^{-2}$  in the COS spectra used here. For example, for a typical  $S/N$  ratio of  $\sim 10$ , the  $5\sigma$  upper limit for non-detection of Ne VIII  $\lambda 770$  line is  $\log N(\text{Ne VIII}) (\text{cm}^{-2}) < 13.66$  for  $b$ -parameter of  $100 \text{ km s}^{-1}$ . Here the assumed  $b$  value (i.e.  $100 \text{ km s}^{-1}$ ) is typical for mini-BAL system. The previously reported associated Ne VIII systems (see e.g. Table 8) are all showing  $N(\text{Ne VIII}) > 10^{15} \text{cm}^{-2}$ .

### 6.5 Column density ratios and ionization state

In different sub-panels of Fig. 21, various column density ratios are plotted as a function of  $\log N(\text{Ne VIII})$ . The *stars* and the *circles* in the bottom panel of Fig. 21 are representing the  $N(\text{Ne VIII})/N(\text{O VI})$  ratios in associated and intervening Ne VIII absorbers respectively. A Spearman rank correlation analysis shows ( $\rho_s = 0.75$ ) a  $2.3\sigma$  level correlation between Ne VIII and O VI column densities in associated absorbers. When we include the intervening absorbers in the analysis, the correlation becomes even tighter (e.g.  $\rho_s = 0.91$  and  $\rho_s/\sigma = 3.5$ ). The median value of  $\log N(\text{Ne VIII})/N(\text{O VI})$  ratio for the associated absorbers is  $0.11 \pm 0.50$ . Under photoionization equilibrium it corresponds to the ionization parameter  $\log U = 0.4 \pm 0.2$ . Under collisional ionization equilibrium the above ratio is reproduced when  $T \sim 10^{5.8} \text{ K}$  and  $\log U \leq -2$ . Based on the present data we are not in a position to disentangle among different ionization mechanisms. However, detection of absorption line variability and its relationship to the continuum variation will enable us to distinguish between the two alternatives. For a flat SED, the ionization parameter, density ( $n_H$ )

and distance between the absorber and the QSO are related by,

$$\log \left( \frac{n_H}{10^5/\text{cc}} \right) = \log L_{912\text{\AA}}^{30} - \log \left( \frac{r}{100\text{pc}} \right)^2 - \log U - 1.25 \quad (4)$$

where,  $\log L_{912\text{\AA}}^{30}$  is the monochromatic luminosity of the QSO at the Lyman continuum in units of  $10^{30} \text{ erg s}^{-1} \text{ Hz}^{-1}$ . The density estimation using absorption line variability or fine-structure excitations will enable us to get the location of the absorbing gas with respect to the central engine. This will allow us to estimate the kinetic luminosity of the outflow which is very crucial for probing the AGN feedback (e.g., Moe et al. 2009; Dunn et al. 2010; Bautista et al. 2010; Borguet et al. 2012b).

We have mentioned earlier that the intervening absorbers are showing systematically lower values of  $N(\text{Ne VIII})$ . But, as far as  $N(\text{Ne VIII})/N(\text{O VI})$  ratio is concerned there is very little difference between associated and intervening absorbers. For example, the median values of  $\log N(\text{Ne VIII})/N(\text{O VI})$  ratios in intervening and associated absorbers are,  $-0.45 \pm 0.50$  and  $0.11 \pm 0.50$  respectively, consistent within  $1\sigma$  level. Naively this implies a large ionization parameter even for the intervening systems. In case of intervening Ne VIII absorbers models of collisional ionization are generally proposed, as photoionization by the extragalactic UV background (Haardt & Madau 1996) requires unusually large cloud sizes (Savage et al. 2005; Narayanan et al. 2009, 2011). Thus similar ratios seen between associated and intervening systems and between different components in an associated system as in the case of Muzahid et al. (2012b) favour collisional ionization in the associated absorbers as well.

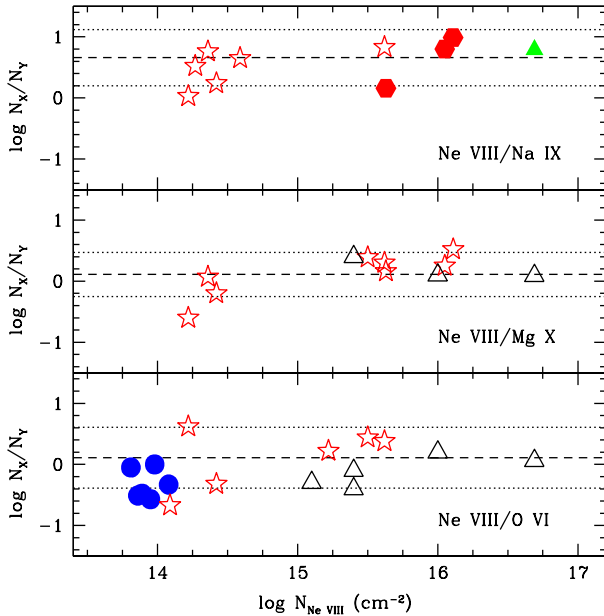
Further, we notice a strong correlation between  $N(\text{Ne VIII})$  and  $N(\text{Mg X})$  (i.e.  $\rho_s = 0.90$  and  $\rho_s/\sigma = 2.4$ ). The median value of  $\log N(\text{Ne VIII})/N(\text{Mg X})$  is found to be  $0.11 \pm 0.36$  (see middle panel of Fig. 21). These observed ratios correspond to a very narrow range in gas temperature (i.e.  $T \sim 10^{5.95 \pm 0.03} \text{ K}$ ) under CIE or very narrow range in ionization parameter (i.e.  $\log U \sim 0.8 \pm 0.2$ ) under photoionization [see panel (D) of Fig. 12]. Given the high ionization parameter and low neutral hydrogen column density (i.e.  $< 10^{14.5} \text{ cm}^{-2}$  in most of the cases), the predicted total hydrogen column density is too low (i.e.  $N(\text{H}) < 10^{20.5} \text{ cm}^{-2}$ ) to produce significant continuum optical depth in the soft X-ray regime.

In the top panel of Fig. 21 we show  $N(\text{Ne VIII})/N(\text{Na IX})$  ratio as a function of  $N(\text{Ne VIII})$  in logarithmic scale. It is interesting to note that the three systems, where we detect Na IX absorption (i.e. solid hexagons in the plot), are all showing  $\log N(\text{Ne VIII}) \gtrsim 15.60$ . The solid (green) triangles in this panel represents the tentative detection of Na IX reported by Arav et al. (1999b), which also shows  $\log N(\text{Ne VIII}) > 15.60$ . We notice that  $\log N(\text{Ne VIII})/N(\text{Mg X})$  and  $\log N(\text{Ne VIII})/N(\text{O VI})$  are roughly similar between the systems with and without detectable Na IX absorption. This clearly means that the lack of Na IX detection can be attributed to low  $N(\text{H})$ .

### 6.6 Multiple phases in Na IX absorbers

We report secure detections of Na IX absorption in three associated Ne VIII systems for the first time. These systems show signatures of multiple component structure. Photoionization models with  $\log U \sim 1$  explain the Na IX phase of the absorbers. However these models require Na abundance being enhanced by a factor of 4–7 with respect to Mg. Standard chemical evolution models do not predict such large enhancement of Na over Mg (see Fig. 18 of Timmes et al. 1995, and Fig. 6 of Venn et al. (2004)). The pho-





**Figure 21.** Column density ratios (Ne VIII/O VI, *bottom*; Ne VIII/Mg X, *middle*; Ne VIII/Na IX, *top*) as a function of  $N(\text{Ne VIII})$ . The open triangles and (blue) filled circles are from Table 8 and Table 9 respectively. In the top panel all the points apart from (green) triangle is from this paper. The solid hexagon indicate Na IX detections. The solid (green) triangle represents the tentative Na IX detection by Arav et al. (1999b). The mean values and corresponding scatters, only for data points from our sample, are shown in each panel by horizontal dashed and dotted lines respectively. Here we assumed all the limits as measurements.

toionization models also suggest a typical density of the absorbing region varying by up to a factor 10 along the transverse direction. As photoionization predicts roughly same temperature for the range of ionization parameters probed by low and high ions, different phases cannot be in pressure equilibrium. On the contrary, if collisional excitations are important then one may not need an enhancement of Na, provided the gas temperature  $T = 10^{5.9}$  K. In the case of CIE the low ionization phase requires  $T \sim 10^{5.2}$  K. Therefore, a factor  $\sim 5$  density difference between two phases is needed for the gas to be in pressure equilibrium. In the case of CIE, absorbing gas has to be far away from the QSO for the gas to be unaffected by the QSO radiation. Therefore it is important to identify the source of energy that maintains the high temperature of the gas. Probing the optical depth variability and presence of fine-structure transitions with new *HST*/COS observations will allow us to make good progress in this direction.

At last, we note that the element Na has not been incorporated in the non-equilibrium collisional ionization calculations so far. For the metallicity as measured in our sample, non-equilibrium effects would be important and can provide more realistic models of Na IX absorbers. Therefore, inclusion of Na in non-equilibrium calculations will be very useful.

## 7 SUMMARY & CONCLUSIONS

We present a sample of new class of associated absorbers, detected through Ne VIII  $\lambda\lambda 770, 780$  absorption, in *HST*/COS spectra of intermediate redshift ( $0.45 \leq z \leq 1.21$ ) quasars. We searched for Ne VIII absorption in the public *HST*/COS archive of QSOs with

$S/N \geq 10$  and emission redshift  $z_{\text{em}} > 0.45$ . There were total 20 QSO sight lines in the *HST*/COS archive before February 2012, satisfying these criteria. Seven of these QSOs are radio bright. The signatures of associated Ne VIII absorption are seen in 40% (i.e. 8 out of 20) of the lines of sight, with 10 secured and 2 tentative Ne VIII systems detected in total. None of them are towards radio bright QSOs. The associated absorbers detected towards QSO HE 0226–4110 and QSO HE 0238–1904 were previously reported by Ganguly et al. (2006) and Muzahid et al. (2012b) respectively. Here we summarize our main results.

(1) Majority of the Ne VIII absorbers are detected with outflow velocities  $\lesssim 5000 \text{ km s}^{-1}$ . The highest velocity system shows  $|v_{\text{ej}}| \sim 19,000 \text{ km s}^{-1}$ . Medium resolution COS spectra allow us to probe the component structure of Ne VIII absorption in most of the systems. The line spread of Ne VIII absorption is found to be in the range  $100 \leq \delta v (\text{km s}^{-1}) \leq 1000$ , suggesting that these absorbers are most likely mini-BALs. The Doppler parameters measured in individual components (with median  $58.7 \pm 31.7 \text{ km s}^{-1}$ ) indicates domination of non-thermal motions.

(2) We detect Mg X absorption in 7 of 8 Ne VIII systems when the lines are not blended and are covered by the observations. Moreover, we report first secure detections of Na IX absorption in three highest velocity systems in our sample. All three Na IX systems show high  $N(\text{Ne VIII})$  (i.e.  $> 10^{15.6} \text{ cm}^{-2}$ ). The measurements and/or limits on the column densities of different ions, detected in these Na IX absorbers, require very high ionization parameter (i.e.  $\log U \geq 0.5$ ) and high metallicity (i.e.  $Z \geq Z_{\odot}$ ) when we consider single phase photoionization models. However, ionization potential dependent covering fraction seen in these absorbers suggests kinematic coincidence of multiphase gas with higher ionization species having higher projected area. Given the high value of ionization parameter ( $\log U$ ) and observed low  $N(\text{H I})$ , the model predicted  $N(\text{H})$  is too low (i.e.  $< 10^{20.5} \text{ cm}^{-2}$ ) to produce any significant continuum optical depth in the soft X-ray regime. The observed  $N(\text{Mg X})/N(\text{Na IX})$  ratios, under single phase photoionization scenario, require a factor  $\gtrsim 5$  enhancement of Na abundance with respect to Mg. However, such enhancement is not required in CIE models provided gas temperature is  $T \geq 10^{5.9}$  K. In the case of CIE, the low ions require a different phase with temperature  $T \sim 10^{5.2}$  K suggesting a factor of  $\sim 5$  difference in density between two gas phases to be in pressure equilibrium.

(3) We notice a very narrow range in the column density ratios of high ions (i.e. O VI, Ne VIII, Mg X etc.). This suggests a narrow range in ionization parameter (temperature) under photoionization (CIE). The median value of  $\log N(\text{Ne VIII})/N(\text{O VI}) = 0.11 \pm 0.50$  as measured in our sample is comparable to that measured in the intervening Ne VIII absorbers within the measurement uncertainties. In case of intervening Ne VIII absorbers collisional ionization is generally proposed, as photoionization by the extragalactic UV background requires unusually large cloud sizes. Indeed, CIE can play an important role in deciding the ionization structure of the absorbing gas in our sample as well. However, for CIE to be dominant, gas cloud has to be far away from the QSO. In that case it is crucial to understand sources of thermal and mechanical energy and the stability of the absorber. Variability study with repeated *HST*/COS observation is needed to make further progress on these issues.

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